FERMILAB-LU-228

FERMILAB
ACCELERATOR DIVISION
MECHANICAL SUPPORT DEPARTMENT

Linac Upgrade Module Temperature Control System

SPECIFICATION #

1302 -ES- 296036

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DATE ISSUED:
10/14/93

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LINAC UPGRADE MODULE TEMPERATURE CONTROL SYSTEM

INTRODUCTION

The main objective of the temperature control system is to control the resonant frequency of the cavity. Each module consists of four sections connected with bridge couplers driven with a 12 MW Klystron. Each section is a side coupled cavity chain consisting of 16 accelerating cells and 15 side coupling cells. For the Linac Upgrade seven modules are used. Each module has a separate temperature control system. In addition there are two transition sections and the debuncher section.

SUPPORTING DOCUMENTS

The drawings below may be used as reference should questions concerning detailed design of the water skids and piping installation arise. The drawings are kept at the Mechanical Support Department (MSD) Mechanical Drafting area.

LINAC UPGRADE
Linac Temperature Controlled System Piping
Tunnel Installation- Module 0 to 7
0260.000-ME-300570-1 to -7 (7 Drws.)

LINAC UPGRADE WATER SYSTEM
Linac Temperature Control System Piping
Basement Installation
0260.000-ME-300558

LINAC UPGRADE
Transitions and Debuncher Water Mixing Skid
Slide Assembly
0260-ME-61941 Rev B

LINAC UPGRADE
Module Temperature Control Skid
New Design Layout
0260.000-ME-300470 Rev B

LINAC UPGRADE
Module distribution Skid
Assembly
0260.000-ME-300549 Rev B

LINAC UPGRADE
Module Piping
Assembly
0231.000-ME-61814

Please refer to Appendix- B for the Instrumentation and Control electrical drawings list.

Please also refer to the following documents:

CRISP, J., " Temperature Control Feedback Loops for the Linac Upgrade Side Coupled Cavities at Fermilab", Fermilab TM 1698, Oct. 1990.

CRISP, J., SATTI, J., " Fermilab Linac Upgrade Side Coupled Cavity Temperature Control System", 1991 IEEE Particle Accelerator Conference, p 3189.

MODULE POWER AND COOLING REQUIREMENTS

Figure 1 shows the approximate power and cooling requirements for a typical module. About 82 KW of electrical power is used per module. Of this power, about 94 % goes into the cooling water, 4% into the proton beam, and the remaining 2% is removed by convection into the room air.

There are two distinctive cooling systems. The RF power supplies and the Klystrons are cooled from the RF Water System installed in the Linac Gallery Annex. This cooling system removes the majority of the power. About 24% of the RF heat is dissipated into the copper cavities. This heat is removed by the Module Temperature Control System which is described in this paper

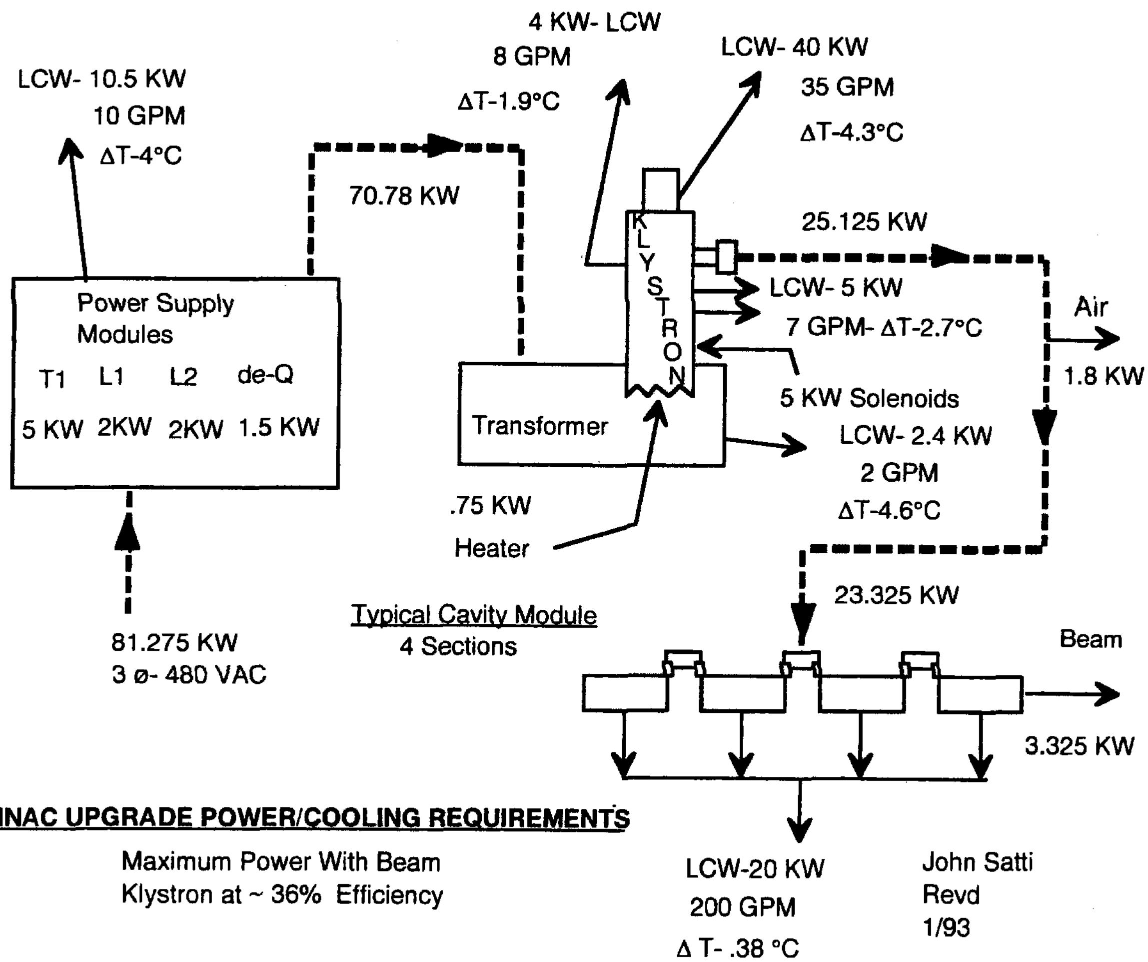
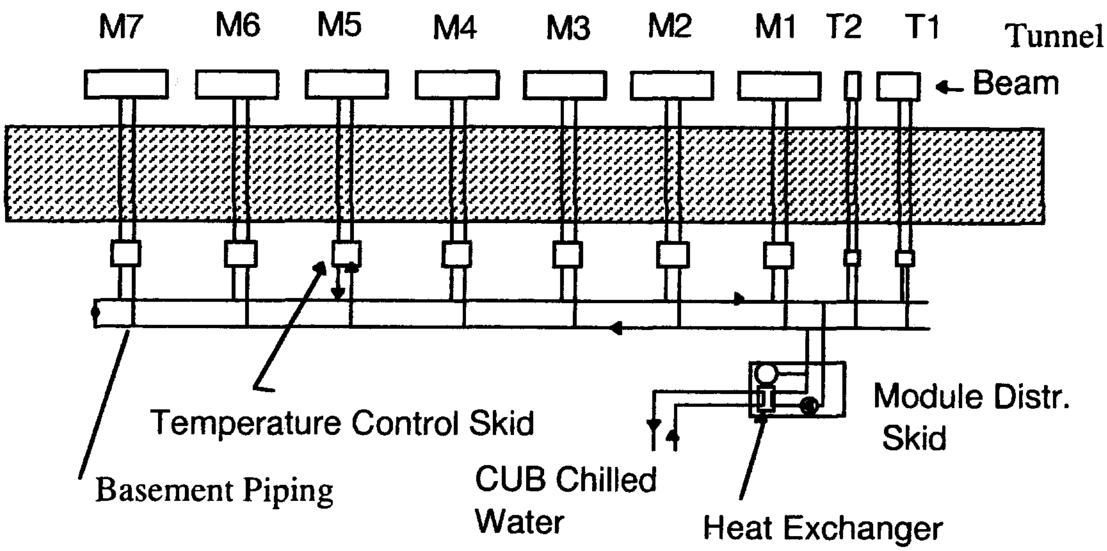


Fig. 1

MODULE TEMPERATURE CONTROL SYSTEM

The temperature in each module is controlled by mixing chilled water with the water circulating between the cavities and the water skids located outside the radiation enclosure. The temperature controlled water skids for the seven modules and the two transition sections are located in the Linac Lower Level. Here also is located the Module Distribution Skid which provide the chilled low conductivity water (LCW). In this later skid, the heat is removed through a heat exchanger to the CUB chilled water system. Figure 2 shows a simplified schematic of the water systems in the Linac Lower Level. The Debuncher cavity temperature control skid is located in the Booster West Gallery; this design is similar to the T2 transition system.



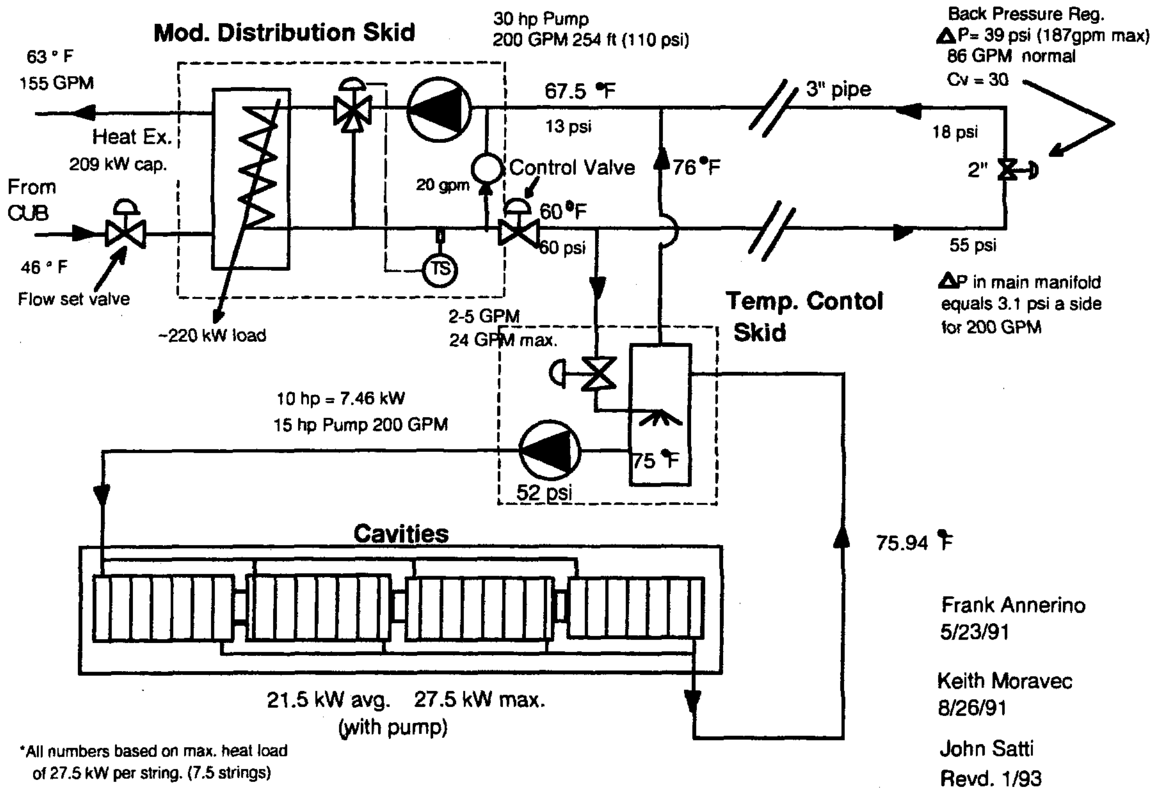
MODULES TEMPERATURE CONTROL SYSTEM
Linac Lower Level

J. Satti 1/93

Fig. 2

CHILLED LCW AND TEMPERATURE CONTROLLED SYSTEM

The Module Distribution Skid provides 60° F LCW to the module and transition temperature control skids. Figure 3 shows a simplified schematic with expected flows, pressures, and temperatures. With all the components installed, final tuning of the system is always required. The pump is generally sized for maximum operating conditions. In this case, the cooling required will vary depending on the operation of the cavities and also during the start-up transient heat transfer demand. To compensate for the various water flows required for cooling, a back-up pressure regulating valve is installed at the end of the 3" pipe manifold. The valve is designed to keep constant the supply water pressure by compensating for the change in flows through the Temperature Control Skids.



CHILLED LCW AND TEMPERATURE CONTROL SYSTEM

Fig. 3

MODULE DISTRIBUTION SKID

The Module Distribution Skid schematic is shown in figure 4. This skid is design to deliver 60° F low conductivity water (LCW) for cooling the modules and the transition sections.

A 170 gallons capacity tank is used for water expansion and reservoir. The top of the tank is filled with nitrogen gas. A magnetic water level indicator is installed along the side of the tank with a low level alarm indicating a possible water leak.

The system has two pumps. One pump is operational and the second one is in stand-by mode with manual switch-over for maintenance. Each pump has an independent electrical starter. For safety, the pumps have local controls only.

The temperature of the LCW is controlled with a tree-way valve which divert the flow through a plate and frame heat exchanger. Heat is transferred to the industrial chilled water (ICW) returning to the Central Utility Building (CUB). Normal temperature of the ICW is 50° F.

To keep the water at a low conductivity (about 5 M-Ohms-cm. specific resistance) , few gallons per minutes are by-passed through mixed bed deionizers bottles. Five microns cartridge filters keeps the water clean . After the original flushing , about 8 Gpm is needed for operation polishing.

Typical temperatures, pressures, and flows are shown in the schematic. From all the instrumentation's meters available on the skid, seven have remote readouts. There are five pump motor interlocks which protect the system from malfunction. A turbine flow meter, installed on the return flow pipe, is the main interlock which is also connected to the Linac Control System. High and low water level interlocks are installed next to the tank. There are two temperatures interlocks. The Klixon type is installed close to the pump discharge, and it is a back-up for a thermocouple type installed downstream of the heat exchanger. Detailed explanation of all the instrumentation and interlocks with electrical diagrams are given in the instrumentation section of this report (Appendix B).

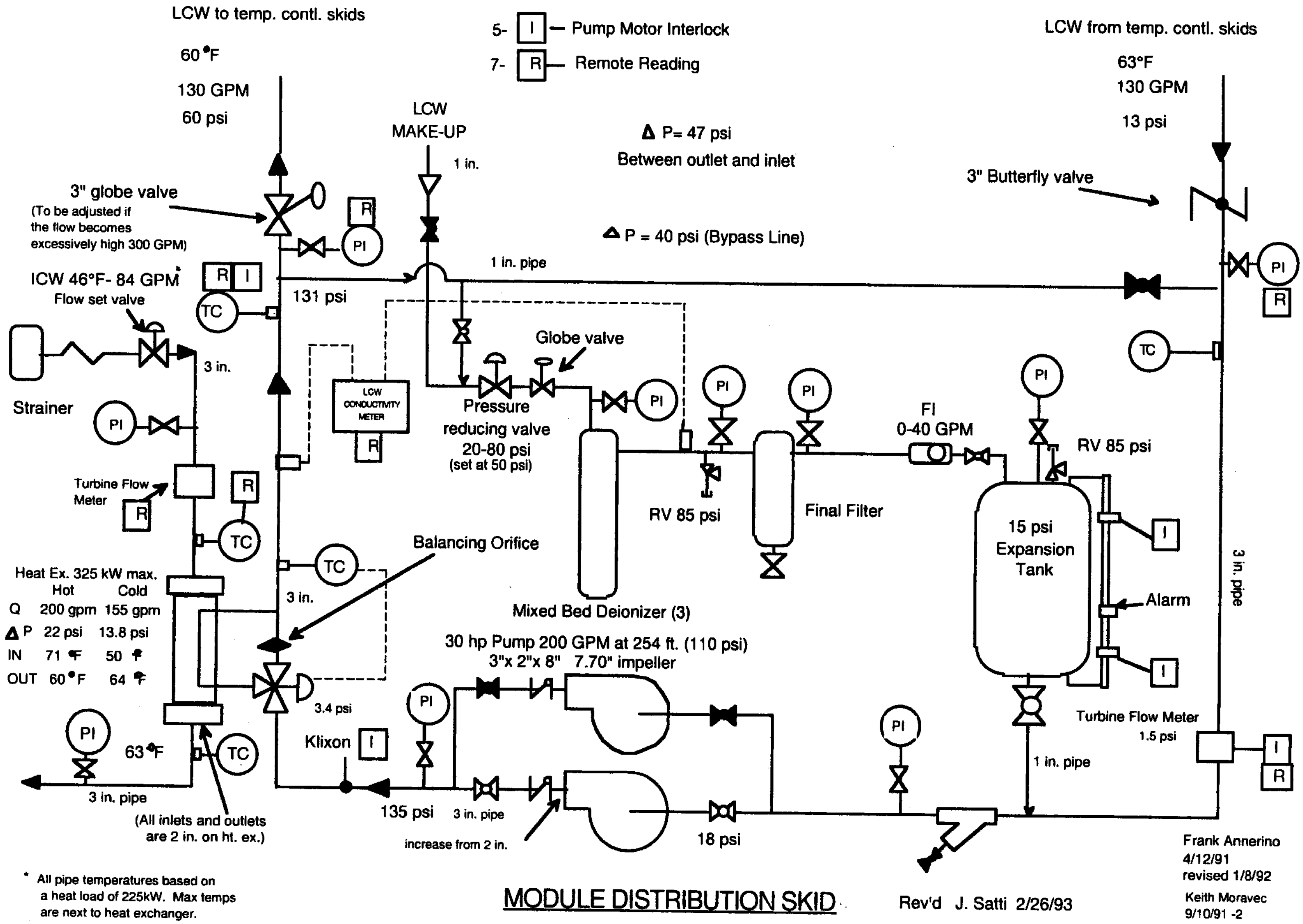
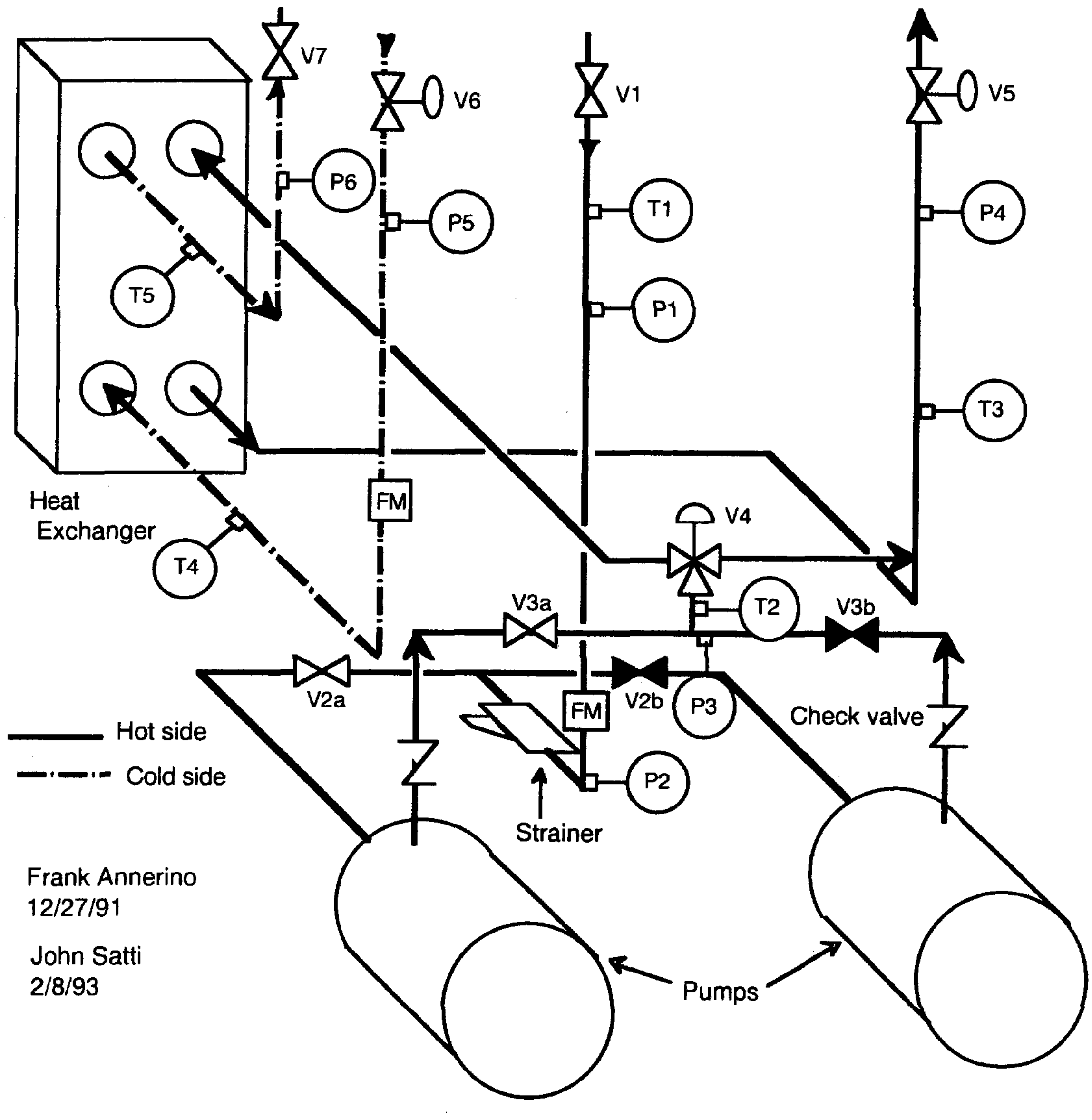

LCW to temp. contl. skids
60 °F
130 GPM
60 psi
5- I — Pump Motor Interlock
7- R — Remote Reading
LCW from temp. contl. skids
63°F
130 GPM
13 psi
LCW MAKE-UP
1 in.
Δ P= 47 psi
Between outlet and inlet
3" Butterfly valve
3" globe valve
(To be adjusted if the flow becomes excessively high 300 GPM)
Δ P = 40 psi (Bypass Line)
1 in. pipe
ICW 46°F- 84 GPM*
Flow set valve
131 psi
3 in.
Globe valve
Strainer
LCW CONDUCTIVITY METER
Pressure reducing valve
20-80 psi
(set at 50 psi)
FI
0-40 GPM
RV 85 psi
Turbine Flow Meter
RV 85 psi
Final Filter
15 psi
Expansion
Tank
Balancing Orifice
Alarm
3 in. pipe
Heat Ex. 325 kW max.
Hot Cold
Q 200 gpm 155 gpm
Δ P 22 psi 13.8 psi
IN 71 °F 50 °F
OUT 60 °F 64 °F
3 in.
Mixed Bed Deionizer (3)
30 hp Pump 200 GPM at 254 ft. (110 psi)
3"x 2"x 8" 7.70" impeller
3.4 psi
Klixon
Turbine Flow Meter
1.5 psi
63 °F
1 in. pipe
3 in. pipe
(All inlets and outlets are 2 in. on ht. ex.)
135 psi
3 in. pipe
increase from 2 in.
18 psi
Frank Annerino
4/12/91
revised 1/8/92
Keith Moravec
9/10/91 -2
* All pipe temperatures based on a heat load of 225kW. Max temps are next to heat exchanger.
MODULE DISTRIBUTION SKID
Rev'd J. Satti 2/26/93
PI
TC
R
I

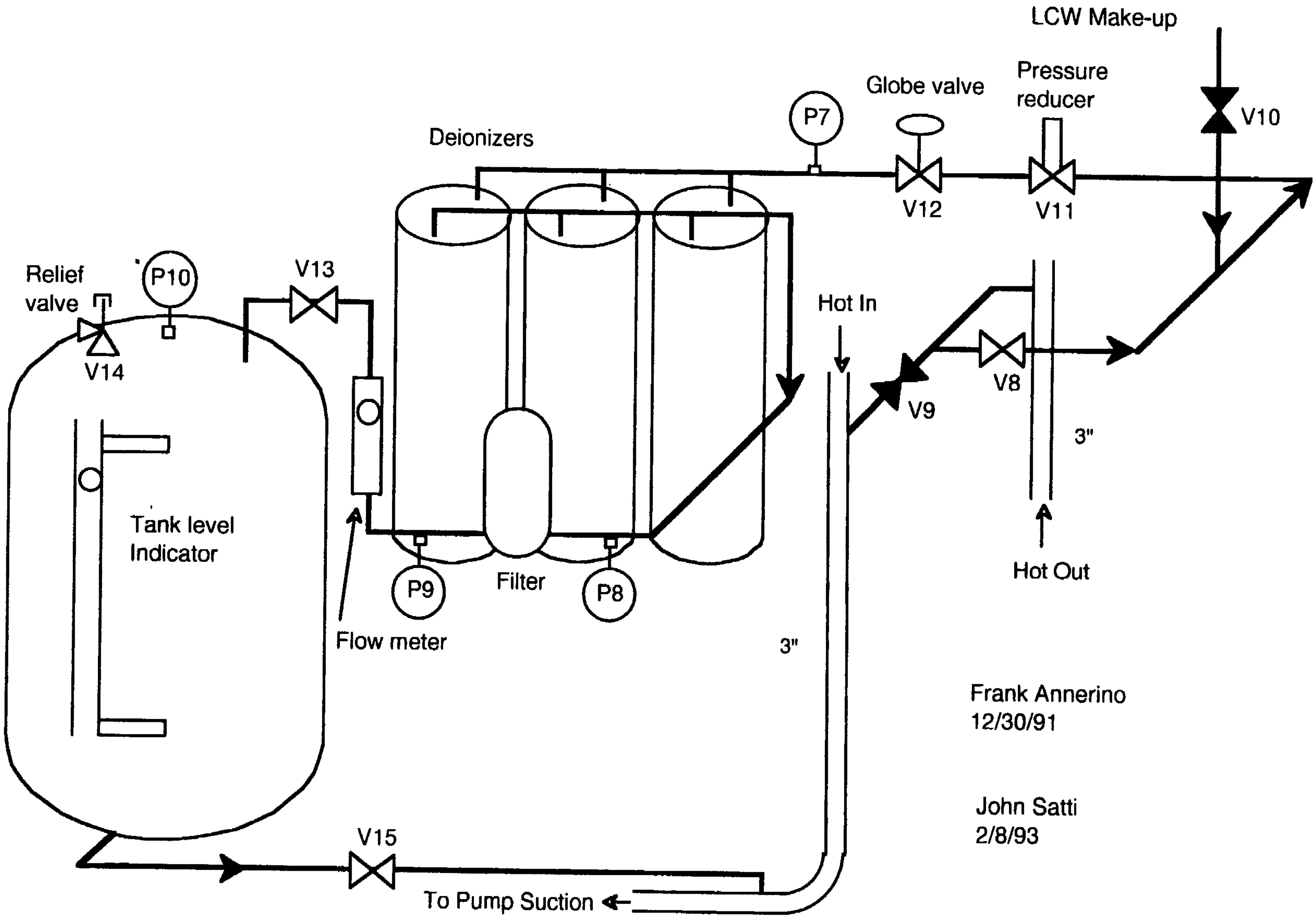
Fig 4

Figure 5 shows the schematic of the 3" piping location in the skid relative to the larger components like the pump, heat exchanger, and the tree-way temperature control valve. The actual location of the instrumentation pick-ups are also shown. Figure 6 shows the 1" piping location with the tank, the bottles and the final filter.



3" PIPING ON LCW COOLING SKID

Fig. 5



1" PIPING ON LCW COOLING SKID

Fig. 6

MODULE TEMPERATURE CONTROL WATER SKID

Each module has one temperature control water skid. The main objective of the temperature loop is to control the resonant frequency by regulating the physical geometry of the cavity. Each copper accelerating cell has a cooling tube brazed in a groove on the circumferential surface. A pump circulates about 160 GPM of water through the four sections on each module. All tubes are hydraulically connected in parallel; and with the same resistance, each tube receives 2.35 GPM of water. A section has 17 cells and the cooling tubes are connected to alternate supply and return manifolds to reduce temperature gradients. The 1/2" outside diameter copper tubes have <u>spiral inner fins</u> to increase the wet surface area for proper heat transfer to the water. A water velocity of 5 Ft/sec in the soft copper tubes is conservative for metal erosion according to the tube manufacture; and the spiral fins induce turbulence flow increasing the thermal film coefficient.

Figure 7 shows a schematic of the Module Temperature Control Skid. Typical water temperatures, flows, and pressures are shown. The temperature in each module is controlled by mixing chilled water in the mixing vessel with the water circulating in the side coupled cavities. The control valve regulates the amount of water (2 to 6 GPM) that is mixed with the flowing water (160 GPM). The electronics of the control loop is explained in detailed in the <u>Temperature (or Frequency) Control System</u> , Appendix A. The mixing vessel is designed to accept 60° F cooling water and to return 75° F to the distribution skid manifold. Strainers are used to protect the turbine flow meters. The skid system is design for 150 psi maximum operating pressure. A relieve valve is mounted on the 6" pipe mixing vessel . A 4 KW heater was installed in case more heat was required to keep the cavities tuned in a no load condition. So far with the existing tunnel temperature, about 7 KW heat from the pump is dissipated into the water and is sufficient to keep the cavities stabled.

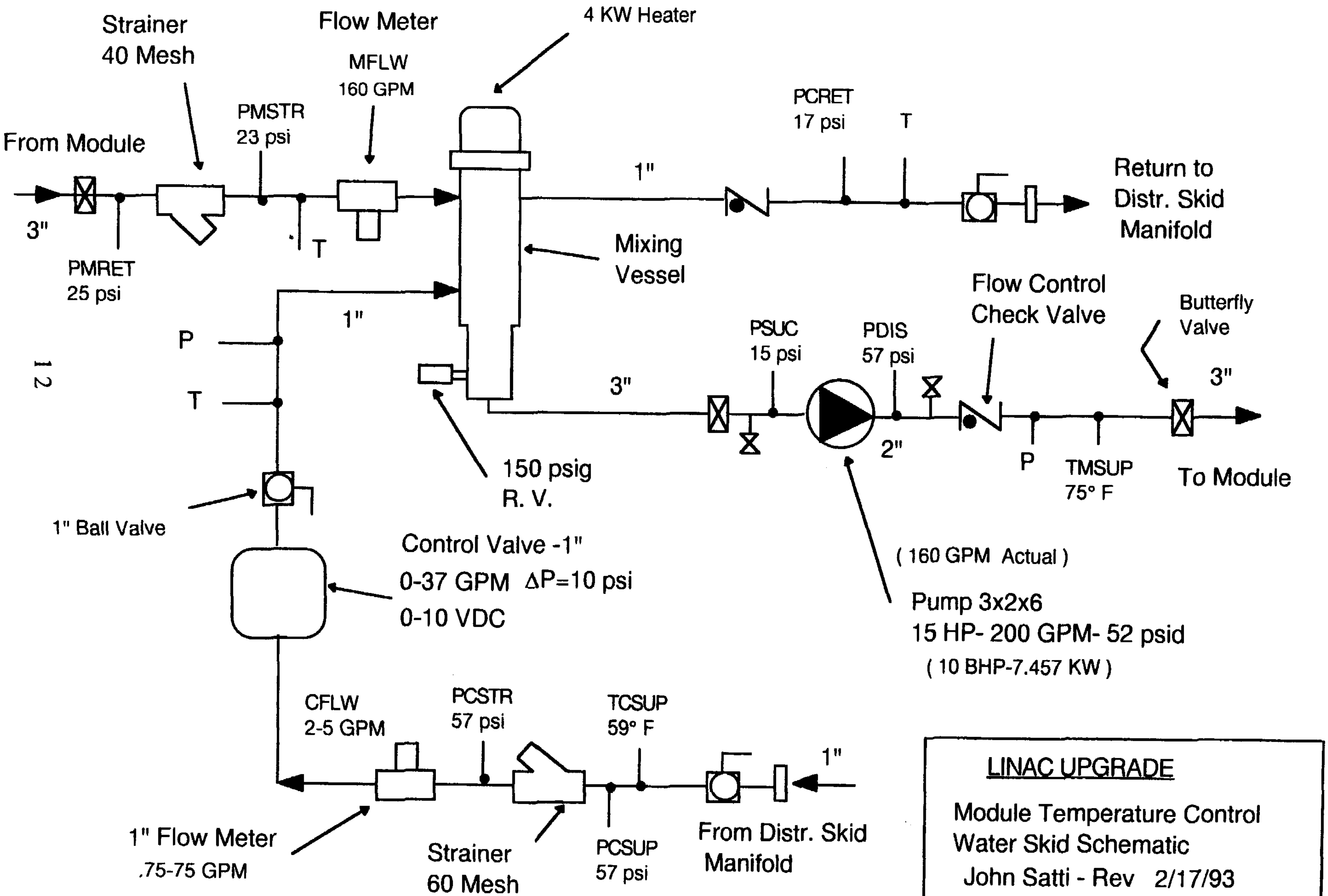

Strainer
40 Mesh
Flow Meter
MFLW
160 GPM
4 KW Heater
PMSTR
23 psi
From Module
3"
PMRET
25 psi
T
Mixing
Vessel
1"
PCRET
17 psi
T
Return to
Distr. Skid
Manifold
1"
P
T
3"
150 psig
R. V.
PSUC
15 psi
PDIS
57 psi
2"
Flow Control
Check Valve
Butterfly
Valve
3"
P
TMSUP
75° F
To Module
1" Ball Valve
Control Valve -1"
0-37 GPM ΔP=10 psi
0-10 VDC
(160 GPM Actual)
Pump 3x2x6
15 HP- 200 GPM- 52 psid
(10 BHP-7.457 KW)
CFLW
2-5 GPM
PCSTR
57 psi
TCSUP
59° F
1"
1" Flow Meter
.75-75 GPM
Strainer
60 Mesh
PCSUP
57 psi
From Distr. Skid
Manifold
LINAC UPGRADE
Module Temperature Control
Water Skid Schematic
John Satti - Rev 2/17/93

Fig. 7

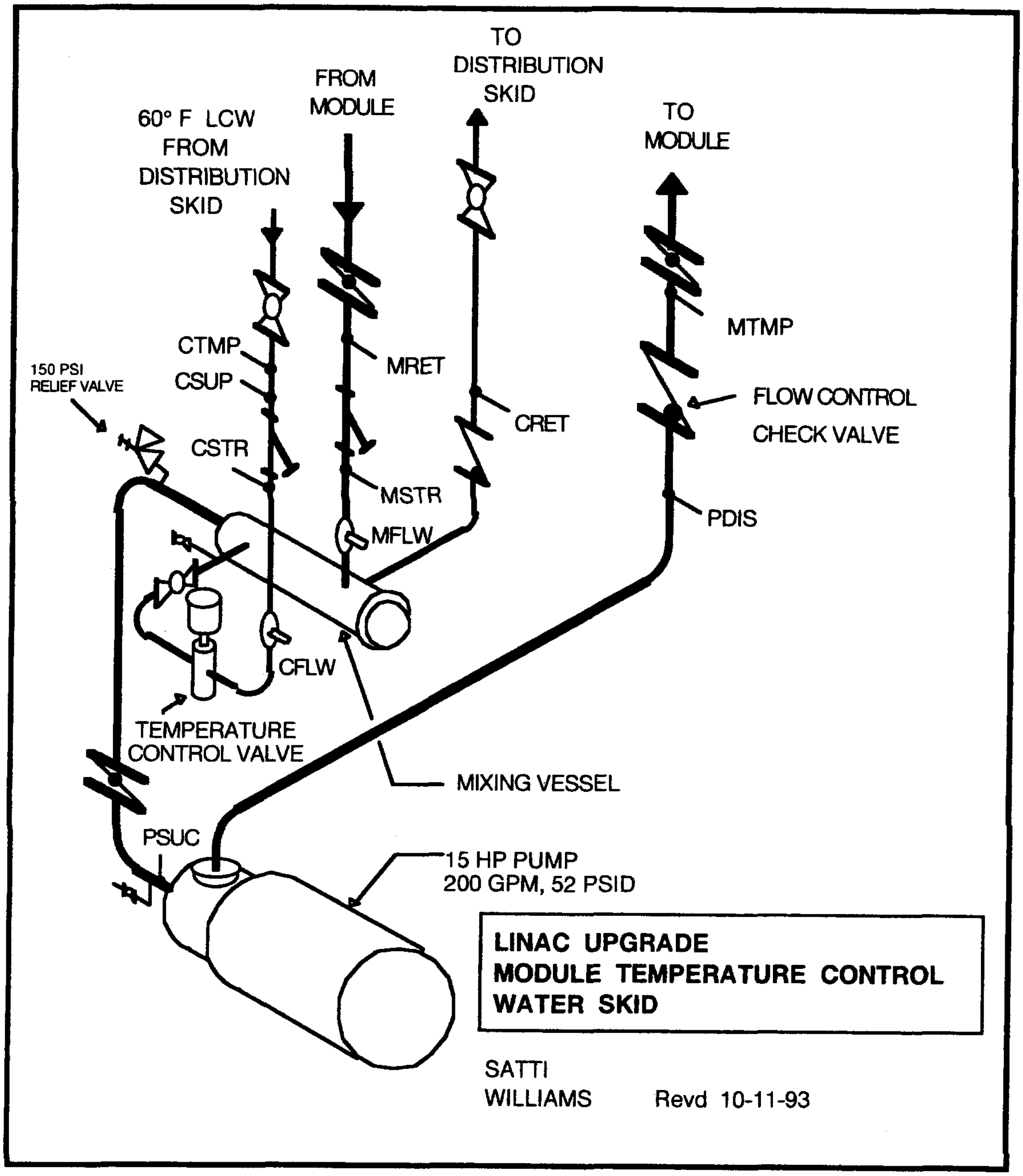
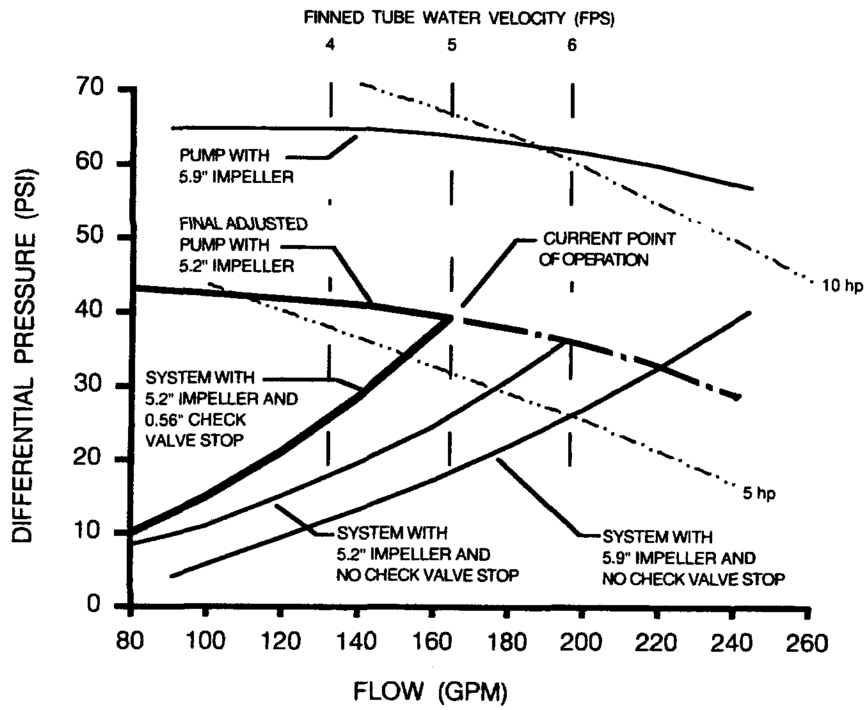


Fig. 8

The above figure is a schematic representation of the piping layout in the Temperature Control Water Skid. This schematic is installed next to the instrumentation panel on the electronic rack mounted on the skid. The computer nomenclature and the location of the instrumentation are shown for reference.

After final pressure regulations and system flow impedance studies, the skid has been adjusted to flow about 160 GPM of temperature regulated water to the module. This was done by reducing the size of the impeller. Final flow adjustment is achieved by using the check valve to control the flow. This is done by using a factory recommended sleeve spacer to limit the opening of the check valve.



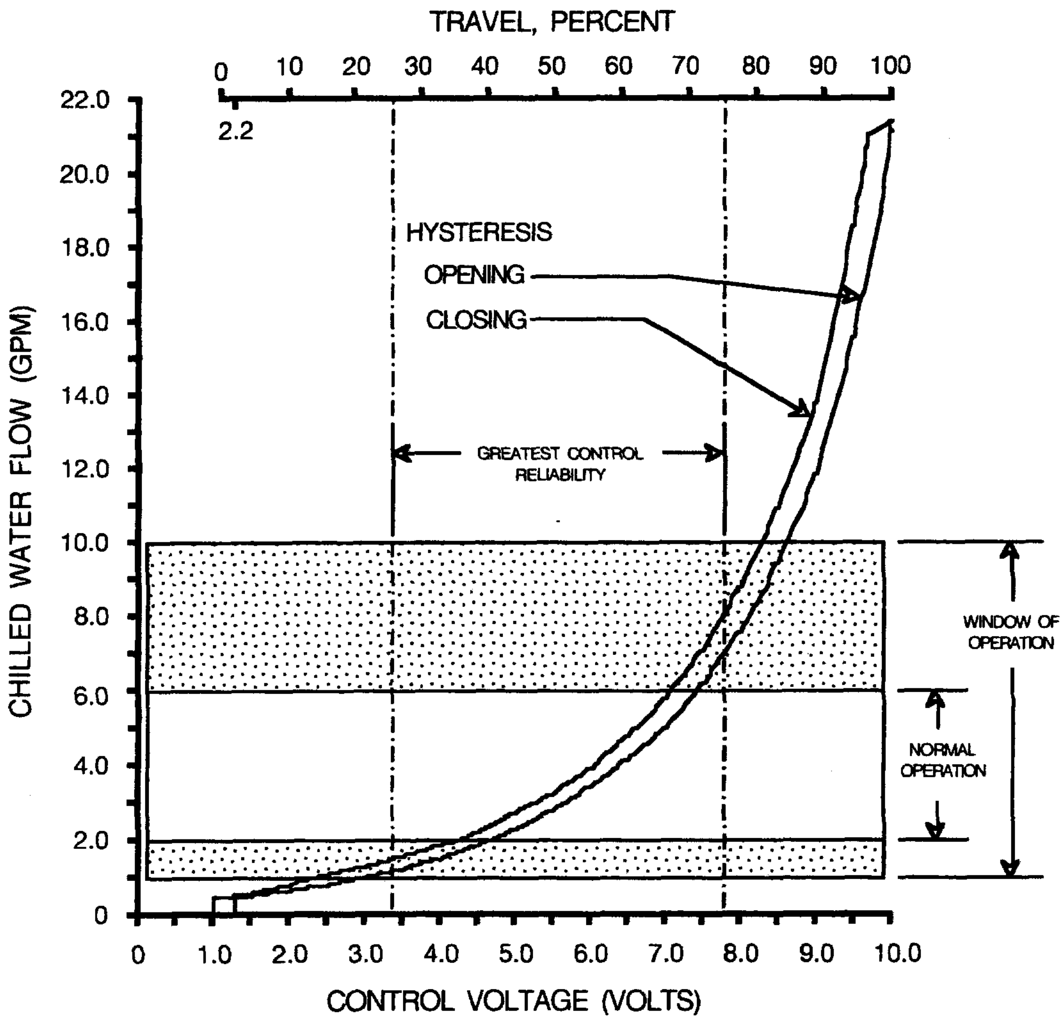
TEST DATA : MODULE #5 LCW MIXING SKID
PUMP AND SYSTEM CURVES FOR FLOW vs. PRESSURE

KARL WILLIAMS 2/18/93

Fig. 9

Figure 9 shows flow test data, for module number 5, before and after adjustment of the pump impeller and the system impedance. All water skids have identical pumps; however due to different pipe lengths, the final flow control for each skid is done using appropriate check valve stops.

The temperature control valve regulates the flow of the 60° F water that is mixed with the 75° F water circulating the cavities. Final adjustments on the valves resulted in changing the orifices to give us a smaller Cv=4.0. This increased the required valve travel for a smaller change in the water flow. The electronic controller liked this because it reduced the dampening cycles required to stabilize the set temperature.



KAMMER TEMPERATURE CONTROL VALVE RESPONSE
WATER FLOW vs. CONTROL VOLTAGE
(Cv = 4.0 EQUAL PERCENTAGE)

KARL WILLIAMS
APRIL 14, 1993

Fig. 10

TRAINING OF WATER EQUIPMENT

The mechanical equipment, in each water skid, has been assembled by the Mechanical Support Department Water Group. The skids were built in our laboratory and moved in the final position where they were connected to the Linac Cavities by the piping contractors.
Building the skids gave our personnel " **on the job training** " of the Temperature Control System. Detailed operations of individual components and their limitations were learned. Participation for improvements, from the technicians, were encouraged especially those which would facilitate the maintenance of the equipment. The drawing listed show the final designs of the skids as built.
When the guidance to the DOE Order will be issued, a training program will be developed in accordance with the Laboratory implementation plan.

SAFETY OPERATION OF SKIDS

The water safety operation is protected from system malfunctions by several interlocks. The volume, the flow, and the temperature of the water are monitored and are interlocked with the electric power source to the pumps. Any readings outside the set range will shut off the pumps.
Below are the list of the interlocks. Detailed electrical design and connections are given in the " Interlock NIM Module" 0231.00-ED-281614 and 0231.00-EC-281098; see also Appendix B "Instrumentation and Control".

Module Distribution Skid Interlocks

1- Expansion Tank High Level (90%)
2- Expansion Tank Low Level (20%)
3- Return LCW Flow (Window, 60 - 300 Gpm)
4- Supply LCW Temperature- Tc (100° F)
5- Klixon Pump/Water Temperature (Op 120°- Cl 90° F)

Module Temperature Control Skid Interlocks

1- Distribution Skid Pump Interlock
2- Module Return LCW Flow (Window, 80-260 Gpm)
3- Klixon Pump/Water Temperature (Op 90°- Cl 80° F)

MAINTENANCE OF WATER EQUIPMENT

Typical equipment inspected monthly:

Close-Coupled Pumps

Check to changes in the sound of a running pump
Changes in bearing temperature
Mechanical seal box leakage

Strainers and Filters

Check pressure drop increase across components

Water Level

Check the water level of the expansion tank in the Module Distribution Skid. The local alarm is set at about 40% level.

LCW Conductivity check (normal resistance 5 M-Ohm-cm.)

Replace DI bottles as required.

Maintenance Required Yearly:

Pump Motors Lubrication and Shaft Rotation Inspection

Clean Stainless Steel Strainers

Change 5 microns Cartridge Filters

Water Sample Analysis

SKID'S INSTRUMENTATION PANEL AND REMOTE READOUTS

Each skid has a local instrumentation meter panel to display the parameters shown on figures 4 and 7. The local readouts are used during maintenance to detect any problems out of the normal operation. Some of the parameters are sent to the computer for remote readouts and temperature controls. The charts below are typical parameters available at the control room and computers along the Linac Gallery Annex.

K7 LCW Copied 10/08/1993 09:06:47

SHOW CHAN 10/08/1993 09:06:33 STATUS 0 ? ????

W7TNOM	27 NOM TEMP	...	26.799	_	C	ON...
W7TSET	27 TEMP LP SET	*	26.401	_	C	
W7TA	27 SECTION A TEMP	*	26.455	_	C	
W7TB	27 SECTION B TEMP	*	26.342	_	C	
W7TC	27 SECTION C TEMP	*	26.404	_	C	
W7TD	27 SECTION D TEMP	*	26.383	_	C	
W7CTMP	27 CLCW SUP TEMP	...	14.996	_	C	
W7MTMP	27 MOD SUP TEMP	*	25.769	_	C	
W7PSUC	27 PUMP SUC PRES	*	21.368	_	PSI	
W7PDIS	27 PUMP DIS PRES	...	60.714	_	PSI	
W7MRET	27 MOD RET PRES	...	24.373	_	PSI	
W7MSTR	27 MOD STRN PRES	*	0.887	_	PSI	
W7CSUP	27 CLCW SUP PRES	...	56.429	_	PSI	
W7CSTR	27 CLCW STRN PRES	...	0.073	_	PSI	
W7MFLW	27 MODULE FLOW	*	164.453	_	GPM	
W7CFLW	27 CLCW FLOW	*	3.651	_	GPM	
W7VSET	27 CLCW VALVE	*	6.320	_	VOLT	
W7FSET	27 FLOW LP SET	*	3.714	_	GPM	

Typical Module Temperature Control Skid Remote Parameter Readouts

Distribution LCW Copied 10/08/1993 15:16:10

SHOW CHAN 10/08/1993 15:15:36 STATUS 0 ? ????

W1DTC1	CHILL IN TEMP	*	42.725	_	DEGF
W1DTC2	LCW SUPPLY TEMP	*	61.003	_	DEGF
W1DP1	SUPPLY PRESSURE	*	127.963	_	PSI
W1DP2	RETURN PRESSURE	*	18.882	_	PSI
W1DRES	RESISTIVITY	*	3.329	_	M/CM
W1FLOW	CHILLED WATER FL	*	130.182	_	GPM
W1LCWF	CHILLED LCW FLOW	*	129.434	_	GPM

Module Distribution Skid Remote Parameters Readouts

TEMPERATURE (or FREQUENCY) CONTROL SYSTEM

Jim Crisp and John Satti

For a cavity constructed of a single metal, the percentage change in resonant wavelength equals the percentage change in linear dimension, which is proportional to temperature.

Temperature Sensitivity	-14.3 KHz/^{o}C	17.8 ppm/^{o}C of 805 MHz

The total radiation exposer inside the cavity enclosure is expected to be 10^8 rads over the 20 year lifetime of the linac upgrade. To eliminate the effects of radiation damage, the water system is located outside of the enclosure and 200 GPM of LCW, (or low conducting water), is circulated through 200 feet of pipe between the cooling skid and the cavity. The cavity copper temperature is controlled by allowing a measured amount of CLCW, (or chilled LCW), to replace an equal amount of circulating LCW at the cooling skid.

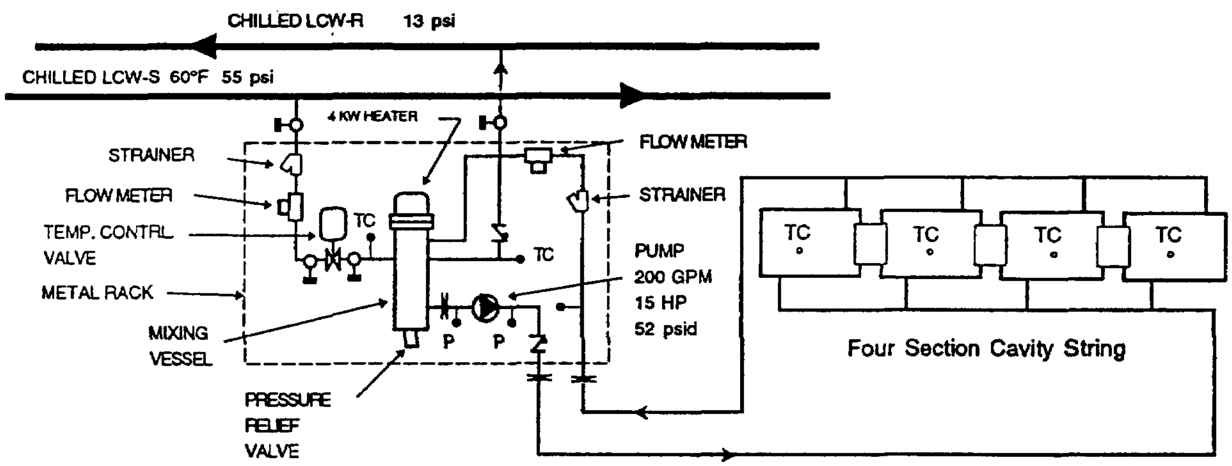


Figure 1. Schematic of cavity string cooling skid.

Under normal conditions there will be a peak rf power of 7.5 MW dissipated in the cavity copper. With a 60 usec pulse width and 15 Hz repetition rate the average rf power is 6.75 KW. In comparison, the pump required to circulate the 200 GPM between the cavity and cooling skid will dissipate 7.5 KW in the water. The cavities are expected to run near room temperature to render radiation and convection losses negligible

Power	rf power	6.75 KW
	pump power	7.5
	total	14.25 KW
Thermal mass	155 Gallons of H_2O	2.44 MJ/^{o}C
	6800 lbs Cu	1.20
	1360 lbs Fe	.28
	total	3.92 MJ/^{o}C

open loop 1/e time constant 2751 seconds 45.9 minutes

The Temperature control loop was implemented inside the local station computer. Since the parameters required to control the cavity temperature should be monitored through the computer already, only software is required to implement the loops. Because the computer also monitors rf power and waveguide to cavity phase, implementing feedforward and the separate phase loop was simplified over a stand alone controller.

The control loop is a simple integral controller selected for its zero steady state error. The closed loop bandwidth is limited to .001 Hz by the 88 second time constant formed by the film coefficient and the 48 second water travel time. The 1/e closed loop time constant of 160 seconds is about 17 times faster than the open loop.

closed loop 1/e time constant 160 seconds

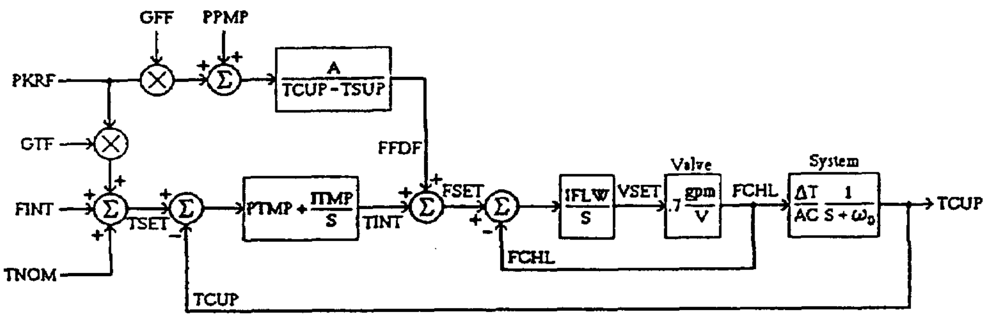


Figure 2. Block diagram of temperature control loop.

Large closed loop bandwidth, or open loop gain, is desirable to reduce the effects of unpredictable changes in the system. Predictable changes can be reduced with feedforward. Accurate control of the CLCW flow was obtained by inclosing the control valve in a separate loop using a precision flow turbine. Measured rf power, cavity, and CLCW temperatures are used to program the flow directly. Over a 4 day period the cavity temperature was observed to change by less than .07 ^{o}C and the resonant frequency by 600 Hz, (.8ppm of 805 MHz).

Water is a good thermal insulator. At the inside surface of the cooling tubes attached to the cavity, water moves slowly which allows a thermal barrier to form. Higher flow rates induce turbulence which reduces the thermal gradient but increases erosion of the cooling tubes. The 1/2 inch copper tubing used on the cavities is internally finned to improve the film coefficient. The resulting thermal resistance is 240 Watts/^{o}C at 2.9 GPM per cooling path, 50% better than smooth copper tube. The 68 cooling paths and the 6.75 KW of rf power conspire to induce a .41 ^{o}C temperature gradient between the cavity surface and the cooling water. The total flow rate of 200 GPM provides a .13 ^{o}C temperature difference between supply and return. The 34

PSI pressure drop across the cavity contributes an additional .06 °C to this difference. To minimize the temperature gradients, supply and return are reversed on neighboring cooling tubes.

The nominal rf power produces a 1.84 °C temperature gradient between the cavity nose cones and the cooling tube. The corresponding frequency change is -14.9 KHz and the 1/e time constant is 43 seconds for a step change in power. The 39 KJ/°C thermal mass of the nose cones represents only 1% of the total system thermal mass. To keep the frequency constant during turn on, 95 KW of cooling, or heating for turn off, would be required to control the temperature of the remaining 99%. A more cost effective solution is to maintain the bulk of the thermal mass at that temperature which provides the desired resonant frequency for nominal power and program the frequency during turn on. Presently the frequency program is calculated by the computer from the cavity temperature and a running average of the rf power. When the calculated frequency is within 2 KHz of the nominal frequency, the program snaps to the nominal value and the phase loop is enabled. The slower phase loop adjusts the cavity operating temperature to minimize the waveguide to cavity phase error.

Recent tests demonstrate that for a step change in power of 1 to 7.5 MW peak, only 50 seconds were required to reach within 2 KHz of the nominal operating frequency. The maximum waveguide to cavity phase error of 3° (2.2 KHz), is well within the 25° range of the low level rf system.

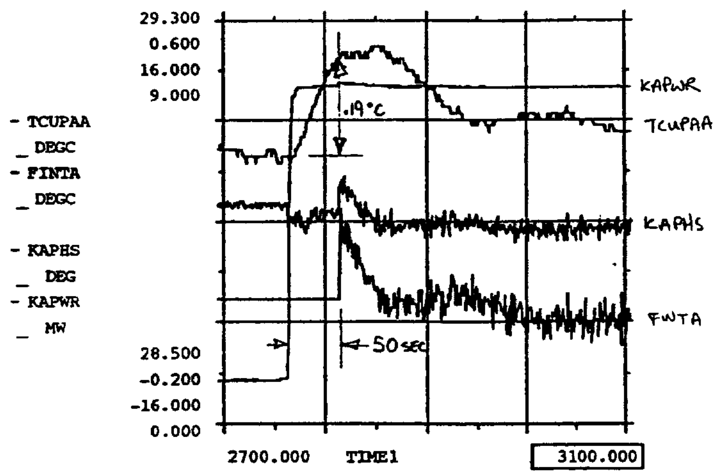


Figure 3. Step response for a 1 MW to 7.5 MW power change.

With 50 mAmps of beam current and 32° accelerating angle, the cavity resonant frequency should be 2.8 KHz below the drive frequency to keep the total cavity current in phase with the voltage. This will require running the cavities .2 °C warmer.

REFERENCES:

Crisp, J., Satti, J., "Fermilab Linac Upgrade Side Coupled Cavity Temperature Control System", to be published, 1991 PAC, May 1990.

Crisp, J., "Temperature Control Feedback Loops for the Linac Upgrade Side Coupled Cavities at Fermilab", Fermilab TM 1698, Oct. 1990.

APPENDIX B

LINAC CAVITY LCW COOLING SKIDS
TABLE OF CONTENTS

MODULE TEMPERATURE CONTROL WATER SKIDS

Instrumentation and Control

Si Fang (10-15-1992)

1. Introduction

The cavity LCW cooling skids consist of a module distribution skid, seven cavity module skids, and two module transition skids. The module distribution skid supplies $60^{\circ}F$ low conductivity water (LCW) to the seven cavity module skids and two module transition skids. The cavity module and module transition skids regulate the cavity temperature at $75^{o}F$.

2. Module Distribution Skid

2.1 Interlocks

2.1.1 LCW Flow Interlock

The module distribution skid LCW flow interlock senses the flow rate of the distribution skid $60^{o}F$ supply LCW. During normal condition, the LCW supply flow rate is approximate 200 GPM. If the flow rate is below 60 GPM, the pump will be shut off by the LCW flow interlock electronics.

2.1.2 Expansion Tank High/Low Level Interlock

The module distribution skid has a expansion tank with two limit switches installed at the upper and lower position of the tank to monitor the water level in the expansion tank. The upper switch is called *Expansion Tank High Level* and the lower switch is called *Expansion Tank Low Level.* The expansion tank high level switch is normally closed and the expansion tank low level switch is normally open. The two limit switches are closed if the water level is within the limits in the expansion tank. If the expansion tank water level is out of the range between the high and low level, the pump will be turned off by the interlock electronics.

2.1.3 Klixon Interlock

A normally closed 90 ^{o}F Klixon has been mounted on the 3 inches pipe near the 30 hp pump motor. If there is no chilled water for heat exchange or the 3 way valve does not work properly, the pump will run hot and the LCW temperature will be increased. The use of the Klixon interlock here is to turn off the pump and protect the distribution LCW system from being overheated. The klixon interlock is a backup for the LCW temperature interlock which the trip temperature is set at $100^{o}F$.

2.1.4 LCW Supply Temperature Interlock

The skid pump is also interlocked with LCW supply temperature. The temperature trip level for the LCW supply temperature interlock has been set at $100^{o}F$.The LCW supply temperature is regulated at $60^{o}F$. If for any reasons that the LCW supply temperature is out of control, the LCW supply temperature interlock will turn off the pump when the LCW temperature is greater than $100^{o}F$.

2.2 Pump Selector

Two 30 HP motors have been installed for the module distribution skid pumps. Only one pump is turned on during operation. The other pump serves as a back up unit. Each pump has its own motor starter which is interlocked with the other pump motor starter.

The pump motor starter can be turned on individually. The pump runs only 15 seconds (0-30 sec. adjustable) if it does not receive a TTL high signal (pump control signal) from the skid interlock chassis in 15 seconds after the pump started. The function of the pump selector is to select the pump motor starter that the pump control signal can go to. The pump selector protects two pumps from turning on at the same time for more than 15 seconds if two pumps are turned on by mistake. The de-selected pump will be turned off at the end of 15 seconds.

2.3 Motor Starters

There are two 30 HP motor starters (ED - 281694) for the module distribution skid. Each motor starter is housed in a NEMA 1 enclosure. A 50 amps circuit breaker, which is for incoming 480 VAC short circuit protection, is lockable and operable from outside of the motor starter enclosure. The motor starter can be turned on and turned off manually by pushing the *ON* and *OFF* switch at the front of the motor starter enclosure. Pump running status is indicated next to the On/Off switches.

The motor starting method is full voltage start. The control voltage is 120 VAC which is from 480/120 VAC transformer installed in the enclosure. The heater of the motor starter protects the pump motor from overloading. When pump #1 is selected and the motor starter *ON* switch is pressed, the contactor coil M1 is energized and M1 contacts are closed so that the coil M1 is on latched. The time delay relay (TDR1), which is operate on relay with 0-30 sec. adjustable, turns off the motor if the motor starter does not receive a pump control active signal (Pump Intlk) from a water flow interlock module by the end of 15 seconds (TDR1 set = 15 sec.) after motor started. The 15 seconds delay gives time for the skid water circulating the system so that the distribution LCW turbine flow meter electronics can measure the flow rate of the water and put out a TTL active high signal to turn on the solid state relay to overwrite the TDR1 contact.

To turn off the motor just simply requires pressing the *OFF* switch. By doing so, the 120 VAC control power is disconnected from the M1 coil and all the M1 contacts are then open.

2.4 LCW Temperature Regulation

The temperature of the supply LCW is regulated at 60 $^{\circ}F$. The temperature regulation system mainly consists of a Honeywell UDC 3000 digital controller and a Worchester three way valve (series 75 electric actuator with AF17-4). The UDC 3000 digital controller controls the opening and closing of the three way valve which regulates the supply LCW temperature at 60$^{\circ}F$. The signal that controls the three way valve is 4 to 20 mA current signal. 20 mA opens the valve completely while 4 mA closes the valve all the way.

In order to use the UDC 3000 digital controller, its software configuration needs to be set for the application. The controller has twelve set up groups, five of which are actually used. These set up groups are called up by pressing the set up key, and the functions within each group are found by pressing the function key. The up and down arrow keys allow you to make changes in each function parameter. Refer to Honeywell UDC 3000 universal digital controller product manual for detail information. The UDC 3000 digital controller for the cavity module distribution skid has been set up in the following manner:

Group Prompt	Function Prompt	Selection or Range of Setting
TURNING	GAIN	30.0
	RATE	0.02
	RSET	1.0
	LOCKOUT	+CONF
SP RAMP	SP RAMP	DISABL
ALGORTHM	CONT ALG	PID A
	OUT ALG	CURRENT
INPUT 1	DECIMAL	XXX.X
	UNITS	DEG F
	IN 1 TYPE	K TC L
	IN 1 HI	1000
	IN 1 LO	-20.0
	PWR FREQ	60 Hz
CONTROL	POWER UP	A LSP
	ACTION	REVERSE

Table 1. Honeywell UDC 3000 Digital Controller Setup

2.5 Module Distribution Skid Parameters Display

The module distribution skid has a meter panel (ED - 281695) to display the skid parameters such as water flow rate, temperature, pressure, and resistivity. Some of these parameters signals are sent to the computer via smart rack monitor for remote readouts.

Water Flow Rate: Hydril turbine flow meter and Hydril series 710 indicator are used to measure the Chilled LCW Flow (FLCW) and Chilled Water Flow (FCHL). The full scale of the turbine flow meter is 600 GPM and the indicator puts out 4 mA at 0 GMP and 20 mA at 600 GPM. A 500 Ω resistor is added across 4 and 5 of the terminal at the back of the indicator to convert the 4-20 mA current signal to 2-10 V voltage signal. The formula to convert the water flow raw volt to GPM reading is:

$$\text{GPM Reading} = 600/8\ (\text{Water Flow Raw Volt} - 2)$$

where the water flow raw volt is the 2-10 V signal from the indicator.

Temperature: Omega DP41-TC-A digital meters are used to measure the Chilled In Temp (T/C1) and LCW Supply Temp (T/C2) temperature. These signals are available for remote readouts. The meters put out 0-10 V for the temperature between -299.9 $^\circ F$ and 1400 $^\circ F$. The formula to convert the temperature raw volt to temperature reading is:

$$\text{Temp Reading } (^\circ F) = (1400 + 299.9)/10\ (\text{Temp Raw Volt}) - 299.9$$

The configuration for the Omega DP41-TC-A digital meters have been set up in the following manner. The unspecified menus here are the factory set values by default (refer to DP41-TC-A product manual for detail).

MENU	SUB MENU 1	SUB MENU 2	DESCRIPTION
INPUT	TC	K	K Thermocouple
DEC PT	FFFF.FF	-	Decimal point
OUT.CNF			Output configuration
	OUT.1=1	-	Analog out enabled
	OUT.2=0	-	0-10V
OT.SC.OF:			Output scale & offset
	READ 1	-299.9	
	OUTPUT 1	00.0000	
	READ 2	1400.0	
	OUTPUT 2	10.0000	
L1 CNF:			Lockout configuration 1
	L1C.7=1	-	Type of input locked
	L1C.8=1	-	Input selection locked
L3 CNF:			Lockout configuration 3
	L3C.7=1	-	OUT.CNF locked
	L3C.8=1	-	OT.SC.OF locked

Table 2. DP41-TC-A Digital Meter Configuration

Omega 650 digital meters are used to indicate the Chilled Out Temp (T/C3) and Return Temp (T/C4) temperature. The meters are $^\circ F/^\circ C$ selectable and they are selected for $^\circ F$ reading unit.

Pressure: Omega DP41-S-A digital meters are used to display the Supply Pressure (P1) and Return Pressure (P2). These signals are available for remote readouts. Each meter has 10 Vdc excitation source for its 0-200 psi (0-100mV) pressure transducer. The meters can be configured for different applications. The Omega DP41-S-A digital meters have been set up as following:

1. 0-100 mV Selection: Jumper S2A, S2F, and S2M

2. 10 V Excitation: Jumper S4A, S2N, and S2T

MENU	SUBMENU	SET VALUE
RDG.CNF	RDG.1=1	-
	RDG.4=1	-
RDG.SC	-	0.00200
RDG.OF	-	000.000
IN CNF	INP.2=1	-
	INP.3=0	-
	INP.6=1	-
	INP.7=0	-
IN.SC.OF	INPUT 1	000.000
	READ 1	000.000
	INPUT 2	200.000
	READ 2	200.000
DEC PT	-	FFF.FFF
OUT.CNF	OUT.1=1	-
	OUT.2=0	-
OT.SC.OF	READ 1	000.000
	OUTPUT 1	00.0000
	READ 2	200.000
	OUTPUT 2	10.000

Table 3. DP41-S-A Digital Meter Configuration

Omega DP 52 digital meters are used to display the pressure of Pump Suction (P3), DI (P4), Pump Discharge (P5), Chilled In (P7), and Chilled Out (P6). The input voltage range of the DP 52 meter is selected for 0-10 V. A amplifier with the gain of 100 has been used with the meter in order to be compatible with 0-100 mV output pressure transducer (0-200 psi). The formula to convert the pressure raw volts to DP 52 meter Psi reading and the setting for the Omega DP52 digital meters is summarized as following:

$$\text{Pressure Reading (psi)} = 20.0 * (\text{Pressure Raw Volt})$$

Function	Jumper Position
0-10 V Input Selection	S3-B
10 Vdc Excitation	S4-A, S2-B,S2-D
Decimal Point XXX.X	S1-C
115 Vac Power	W1,W3

Table 4. DP52 Digital Meter Setup

Resistivity: Foxboro 874RS resistivity meter is used for measuring and displaying the resistivity of the supply LCW. The resistivity is also available for remote readouts. The meter has the resistivity measurement range of 0 to 18.3 $M\Omega \cdot cm$ with the corresponding output of 0 to 10 V. Refer to Foxboro instruction book for detail information. The formula to convert the resistivity raw volt to $M\Omega \cdot cm$ is:

$$\text{Resistivity } (M\Omega \cdot cm) = 18.3/10 * \text{Resistivity Raw Volt}$$

2.6 Skid Pumps Interlock

The module skid pump interlock enables the module skids and module transition skids interlocked with the module distribution skid pump. The pumps of the module and transition skids can not be turned on if the distribution skid pump is off. There is 3 minutes delay for the module and transition skid pumps turn off after distribution skid pump was turned off. The delay gives the distribution pump motor time to be switched with the other distribution pump motor without turning off the module and module transition skids if the distribution pump motor needs to have service.

Refer to Cavity Module Distribution Skid 30 HP Motor Starters (ED-281694) for the explanation in this paragraph. A CH series Potter & Brumfield delay on release relay is used for each motor starter to detect the pump motor ON/OFF status. TDR3 is for pump 1 and TDR4 is for pump 2. If the distribution skid interlocks are o.k and the pump 1 is selected to be turned on, the TDR1 normally open contact closed and turn on the delay on release relay (TDR3) external control switch. The TDR3 normally open contacts closed and sent a pump interlock OK signal to the Module Distribution and Module Skid Pumps Interlock Chassis (in the drawing of ED-281696) to enable motor starter interlock of the module and module transition skids. When the distribution skid pump is turned off, The external control switch is off and the delay period begins. The TDR3 delay has been set at 180 seconds. At the end of the delay period the relay drops out and all the TDR3 normally open contacts open. The distribution and module skid pumps interlock chassis received a pumps interlock NOT OK signal and turn off the pumps of the module skids and the module transition skids. Similarly, The TDR4 does the samething as the TDR3 does if pump 2 is selected. The distribution pumps (pump 1 and pump 2) ON/OFF status is ORed together and the INTLK OUT signal is sent to the distribution and module skid pumps interlock chassis.

When the distribution and module skid pumps interlock chassis received the INTLK active signal(contact closed) from the motor starter, the relay K1, K2, and K3 are energized and their normally open contacts are closed. The closed contacts enable the module and transition skids pump starters interlock circuitry.

3. Cavity Module Skids

3.1 Interlocks

3.1.1 Module Skid Pumps Interlock

The function of the module skid pumps interlock is to protect the module skids from being overheated due to no chilled LCW from the distribution skid. The module skid pumps need to wait for 15 seconds in order to turn on after the distribution skid pump started. The skid pumps are shut off if the distribution skid pump stops running for more than 180 seconds.

3.1.2 Klixon Interlock

A normally closed 90 $^{\circ}F$ klixon has been installed at 2 inches pipe near the 15 HP pump motor for each of the module skids. The klixon interlock here sets the cavity module supply LCW maximum temperature at 90 $^{\circ}F$. The skid pump is shut off by the klixon interlock if the skid out LCW temperature is out of control (higher than 90 $^{\circ}F$). The klixon can reset itself at 80 $^{\circ}F$ after it opened.

3.1.3 Motor Starter Door Interlock

Each motor starter access door is interlocked with its pump to prevent personnel from accidentally touching with 480 VAC. Open the door shuts off the skid pump and removes the 480 Vac power (except the line side of the circuit breaker) from the motor starter enclosure.

3.1.4 Cavity Water Flow Interlock

Each RF station 24 MW power modulator is interlocked with its cavity module cooling water flow. The trip level of minimum water flow rate has been set at 80 GPM and maximum water flow has been set at 260 GPM for the cavity module skids. The cavity water flow interlock signal comes from the module LCW turbine flow meter NIM module (0231.00-EC-281098) located in the cavity module skid and goes to the interlock chassis of LKx-1 rack.

3.2 Motor Starters

There is one 15 HP motor starter (EC - 281697) for each of the cavity module skids. The motor starter is housed in a NEMA 1 enclosure. A 30 amps circuit breaker, which is for incoming 480 VAC short circuit protection, is lockable and operable from outside of the motor starter box. The motor starter can be turned on and turned off manually by pushing the *ON* and *OFF* switch at the front of the motor starter enclosure. Pump running status is indicated next to the On/Off switches.

The pump motor starting method is full voltage start. The control voltage is 120 VAC which is from 480/120 VAC transformer installed in the enclosure. The heater of the motor starter protects the pump motor from overloading. When the *ON* switch is pressed, the contactor coil M is energized and M contactors are closed so that the coil M is on latched. The time delay relay (TDR), which is operate on relay with 0-30 sec. adjustable, turns off the pump if the motor starter does not receive a pump control active signal from a water flow interlock module by the end of 15 sec. (TDR set = 15 sec.) after motor started. The 15 sec. delay gives the time for the skid water flow ready so that the water flow meter electronics can measure the flow rate of the water and put out a TTL active high signal to turn on the solid state relay to overwrite the TDR contact.

To turn off the motor just simply requires pressing the *OFF* switches. By doing so, the 120 VAC control power is disconnected from the M coil and all the M contacts are open.

There are two interlock input twinax connectors mounted on the motor starter enclosure. One input is for module distribution skip pump interlock and the other input is for 90 $°F$ klixon interlock. To turn on the skid pump, the module distribution skid pump interlock, the klixon interlock, and the motor stater door interlock must be completed. Once the skid pump is turned on, it will run for the next 15 seconds and stay on if the cavity water interlock is ready in this 15 seconds.

3.3 Temperature Control

The temperature of the cavity modules supply LCW is regulated at 75 $°F$. The temperature regulation system for each of module skid mainly consists of thermocouple amplifier, pressure amplifier, module LCW turbine flow meter, three way control valve and the computer system for temperature regulation calculation. The 0 to 10V signal from the computer controls the open (10V) and close (0V) of the three way valve for temperature regulation.

3.3.1 Thermocouple Amplifier

The thermocouple amplifier measures the signals from the K type thermocouples and outputs -10V to +10V for the temperature range of 0 $°C$ to 50 $°C$. The -10V to +10V temperature signals are sent to the computer system via smart rack monitor for temperature regulation and remote readouts. There are six channels for the thermocouple amplifier. These channels are summarized in table 5.

Channel	Signal	Description	Unit	Temp. Range	Output range
1	TSECA	Section A Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
2	TSECB	Section B Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
3	TSECC	Section C Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
4	TSECD	Section D Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
5	TCSUP	CLCW Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
6	TMSUP	CAV Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V

Table 5. Thermocouple Amplifier Signals

3.3.2 Pressure Amplifier

The pressure amplifier measures the pressure from the pressure transducers and outputs 0 to +5V for the range of 0 to 200 psi (0 to 150 psi for cavity module skid #3). The pressure amplifier also supplies +5 volts excitation for the pressure transducers. The 0 to +5V pressure signals are sent to the computer system via smart rack monitor for remote readouts.There are six channels for the pressure amplifier. These channels are summarized in table 6.

Channel	Signal	Description	Pressure Range	Output range
1	PSUC	Pump suc pressure	0 - 200 psi	0 - +5V
2	PDIS	Pump dis pressure	0 - 200 psi	0 - +5V
3	PMRET	Mod ret pressure	0 - 200 psi	0 - +5V
4	PMSTR	Mod strn pressure	0 - 200 psi	0 - +5V
5	PCSUP	CLCW sup pressure	0 - 200 psi	0 - +5V
6	PCSTR	CLCW strn pressure	0 - 200 psi	0 - +5V

Table 6. Pressure Amplifier Signals

3.3.3 Module LCW Turbine Flow Meter

The module LCW turbine flow meter measures the water flow rate of cavity module LCW (*FCAV*) and the cavity module skid chilled LCW (*FCHIL*). The module skid pump is interlocked with FCAV. The FCAV minimum flow trip level has been set at 80 GPM and maximum flow trip level is 260 GPM. The module LCW turbine flow meter puts out 0 to 10 V (0 - 600 GPM) for the cavity water flow (FCAV) and 0 - 10 V (0 - 75 GPM) for the module skid chilled LCW (FCHIL).

3.4 Skid Parameters Display

The skid parameters are sent back to the computer system both for temperature regulation and remote readout via the smart rack monitor installed in each of the skids. The thermocouple amplifier module puts out -10 to +10 volt for the temperature of 0 to 50 $^{\circ}C$ (32 $^{\circ}F$ - 122 $^{\circ}F$). The pressure amplifier sends out 0 to 5 volts for the pressure from 0 psi to 200 psi (0 to 150 Psi for cavity module skid #3). The module LCW turbine flow module channel A (cavity module supply LCW flow) has 0 to 10 volts output corresponding to 0 to 600 GPM and channel B (chilled LCW flow) puts out 0 to 10 volts for the chilled LCW flow rate of 0 to 75 GPM.

The skid parameters are also available for local readout. A skid parameters display chassis (ED-281685) has been installed for converting the parameters raw voltage signals to engineering unit readings. The input signals of the parameters display chassis come from the SMR outputs of the thermocouple amplifier, pressure amplifier, and module LCW turbine meter. The scaling circuit of the display chassis scales the inputs properly and the scaled signals are converted to $^{\circ}F$ (temperature), psi (pressure), and GPM (water flow rate) readings by using Acculex DP-352 digital panel meters.

The input voltage range of Acculex DP-352 digital panel meters is $\pm$ 2 V and the full scale input span is 199.9 with DP1 decimal point selection and 1999 without decimal point selection. The equations to convert the voltage signals (temperature, pressure, flow rate) to engineering unit readings are:

$$\text{Temperature Reading } (^{\circ}F) = 4.5 * (\text{Temp Raw Volts} + 10) + 32$$

$$\text{Pressure Reading (psi)} = \text{K1} * \text{Pressure Raw Volt}$$

$$\text{Flow Rate Reading (GPM)} = \text{K2} * \text{Flow Raw Volt}$$

where K1 = 40.0 for the pressure transducers with full scale of 200 psi, K1 = 30.0 for the pressure transducers with full scale of 150 psi, K2 = 60.0 for the cavity module supply LCW flow, and K2 = 7.5 for the chilled LCW flow.

4. Cavity Module Transition Skids

4.1 Interlocks

4.1.1 Transition Skid Pumps Interlock

The function of the transition skid pumps interlock is to protect the transition skids from being overheated due to no chilled LCW from the distribution skid. The transition skid pumps need to wait for 15 seconds to turn on after the distribution skid pump started. The skid pumps are shut off if the module distribution skid pump stopped running more than 180 seconds.

4.1.2 Klixon Interlock

A normally closed 90 $^{\circ}F$ klixon has been installed near the 3 HP pump motor for each of the transition skids. The klixon interlock here sets the cavity transition module supply LCW maximum temperature at 90 $^{\circ}F$. The skid pump is shut off by the klixon interlock if the skid out LCW temperature is out of control (higher temperature). The klixon can reset itself at 80 $^{\circ}F$ after it opened.

4.2 Motor Starters

There is one 3 HP motor starter (EC - 281684) for each of the cavity module transition skids. The motor starter is housed in a NEMA 1 enclosure. A 15 amps circuit breaker, which is for incoming 480 VAC short circuit protection, is lockable and operable from outside of the motor starter enclosure. The motor starter can be turned on and turned off manually by pushing the *ON* and *OFF* switch at the front of the motor starter enclosure. Pump running status is indicated next to the On/Off switches.

The pump motor starting method is full voltage start. The control voltage is 120 VAC which is from 480/120 VAC transformer installed in the enclosure. The heater of the starter protects the pump motor from overloading. When the *ON* switch is pressed, the contactor coil M is energized and M contactors are closed so that the coil M is on latched. The time delay relay (TDR), which is operate on relay with 0-30 sec. adjustable, turns off the pump if the motor starter does not receive a pump control active signal from a water flow interlock module by the end of 15 sec. (TDR set = 15 sec.) after motor started. The 15 sec. delay gives the time for the skid water flow ready so that the water flow meter electronics can measure the flow rate of the water and put out a TTL active high signal to turn on the solid state relay to overwrite the TDR contact.

To turn off the motor just requires simply pressing the *OFF* switches. By doing so, the 120 VAC control power is disconnected from the M coil and all the M contacts are open.

There are two interlock input twinax connectors mounted on the motor starter enclosure. One input is for distribution skip pump interlock and the other input is for 90 $^{\circ}F$ klixon interlock. To turn on the cavity module transition skid pump, the module distribution skid pump interlock and the klixon interlock must be completed. Once the skid pump is turned on, it will run for the next 15 seconds and stay on if the skid cavity water interlock is ready in this 15 seconds.

4.3 Temperature Control

The temperature of the cavity module transition supply LCW is regulated at 75 $^{\circ}F$. The temperature regulation system for each of module skid mainly consists of thermocouple amplifier, pressure amplifier, module LCW turbine flow meter, three way control valve and the computer system for temperature regulation calculation. The 0 to 10V signal from the computer controls the open (10V) and close (0V) of the three way valve for temperature regulation.

4.3.1 Thermocouple Amplifier

The thermocouple amplifier measures the signals from the K type thermocouples and outputs -10V to +10V for the temperature range of 0 °

table 7▷

Channel	Signal	Description	Unit	Temp. Range	Output range
1	TSECA	Section A Temp	°C	0 °C - 50 °C	-10V - +10V
2	TCSUP 1	CLCW Sup Temp	°C	0 °C - 50 °C	-10V - +10V
3	TMSUP 1	CAV Sup Temp	°C	0 °C - 50 °C	-10V - +10V
4	TSECB	Section B Temp	°C	0 °C - 50 °C	-10V - +10V
5	TCSUP 2	CLCW Sup Temp	°C	0 °C - 50 °C	-10V - +10V
6	TMSUP 2	CAV Sup Temp	°C	0 °C - 50 °C	-10V - +10V

Table 7. Thermocouple Amplifier Signals

3.3.2 Pressure Amplifier

The pressure amplifier measures the pressure signals from pressure transducers and outputs 0 to +5V for the range of 0 to 200 psi. The pressure amplifier also supplies +5 volts excitation for the pressure transducers. The 0 to +5V pressure signals are sent to the computer system via smart rack monitor for temperature regulation and remote readouts.There are six channels for the pressure amplifier but only four channels are used for the cavity module transition skid 1 and 2. These channels are summarized in table 8.

Channel	Signal	Description	Pressure Range	Output range
1	PSUC 1	Pump 1 suc pressure	0 - 200 psi	0 - +5V
2	PDIS 1	Pump 2 dis pressure	0 - 200 psi	0 - +5V
5	PSUC 2	CLCW sup pressure	0 - 200 psi	0 - +5V
6	PDIS 2	CLCW strn pressure	0 - 200 psi	0 - +5V

Table 8. Pressure Amplifier Signals

3.3.3 Cavity Module LCW Turbine Flow Meter

Two cavity module transition LCW turbine flow meters are used for cavity module transition skids. Each transition skid module LCW meter measures the flow of the cavity module LCW and skid chilled LCW (FCHIL). The expected nominal flow for FCAV is 50 GPM and the minimum flow trip level has been set at 10 GPM. The transition LCW turbine flow meter puts out 0 to 10 V (0 - 75 GPM) for the cavity module LCW flow (FCAV) and 0 to 10 V (0 - 10 GPM) for the skid chilled LCW flow (FCHIL).

4.4 Skid Parameters Display

The skid parameters for each of cavity module transition skids are sent back to the computer system both for temperature regulation and remote readouts via a smart rack monitor installed in the skid. The thermocouple amplifier module puts out -10 to +10 volt for the temperature of 0 to 50 $^{\circ}C$ (32 $^{\circ}F$ - 122 $^{\circ}F$). The pressure amplifier sends out 0 to 5 volts for the pressure from 0 psi to 200 psi. The transition turbine flow module channel A (cavity module supply LCW flow) has 0 to 10 volts output that is corresponding to 0 to 75 GPM and channel B (chilled LCW flow) puts out 0 to 10 volts also for the turbine meter reading 0 to 10 GPM.

The skid parameters are available for local readouts. A skid parameters display chassis (ED-281691) has been installed for converting the parameters raw voltage signals to engineering unit readings. The input signals of the parameters display chassis come from the SMR outputs of the thermocouple amplifier, pressure amplifier, and transition turbine meters. The scaling circuit of the display chassis scales the inputs properly and the scaled signals are converted to $^{\circ}F$ (temperature), psi (pressure), and GPM (water flow rate) readings by using Acculex DP-352 digital panel meters.

The input voltage range of Acculex DP-352 digital panel meters is $\pm$ 2 V and the full scale input span is 199.9 with DP1 decimal point selection and 19.99 with DP2 decimal point selection. The equations to convert the voltage signals (temperature, pressure, flow rate) to engineering unit readings are:

$$\text{Temperature Reading } (^{\circ}F) = 4.5 * (\text{Temp Raw Volts} + 10) + 32$$

$$\text{Pressure Reading (psi)} = 40.0 * \text{Pressure Raw Volt}$$

$$\text{Flow Rate Reading (GPM)} = \text{K2} * \text{Flow Raw Volt}$$

where K2 = 7.5 for the cavity module supply LCW flow, and K2 = 1.0 for the chilled LCW flow.

DRAWING SUMMARY

SKID	DRAWING TITLE	DRAWING NUMBER
DIST. & CAVITY	CAVITY LCW COOLING SKIDS WIRING BLOCK DIAGRAM	0231.00-ED-281693
MODULE DISTRIBUTION	30 HP MOTOR STARTER CIRCUIT SCHEMATIC	0231.00-ED-281694
MODULE DISTRIBUTION	PARAMETERS DISPLAY PANEL WIRING DIAGRAM	0231.00-ED-281695
MODULE DISTRIBUTION	RELAY RACK WIRNG DIAGRAM	0231.00-ED-281696
MODULE	15 HP MOTOR STARTER CIRCUITRY	0231.00-EC-281697
MODULE	RELAY RACK WIRING DIAGRAM	0231.00-ED-281698
MODULE	PARAMETERS DISPLAY CHASSIS SCHEMATIC	0231.00-ED-281685
MODULE	PARAMETERS DISPLAY BOARD SCHEMATIC	0231.00-ED-281682
MODULE TRANSITION	3 HP MOTOR STARTER CIRCUITRY	0231.00-EC-281684
MODULE TRANSITION	ELECTRONIC CONTROL SYSTEM WIRING DIAGRAM	0231.00-ED-281690
MODULE TRANSITION	PARAMETERS DISPLAY CHASSIS SCHEMATIC	0231.00-ED-281691
MODULE TRANSITION	PARAMETERS DISPLAY BOARD SCHEMATIC	0231.00-ED-281692

TRAINING OF WATER EQUIPMENT

The mechanical equipment, in each water skid, has been assembled by the Mechanical Support Department Water Group. The skids were built in our laboratory and moved in the final position where they were connected to the Linac Cavities by the piping contractors.
Building the skids gave our personnel " **on the job training** " of the Temperature Control System. Detailed operations of individual components and their limitations were learned. Participation for improvements, from the technicians, were encouraged especially those which would facilitate the maintenance of the equipment. The drawing listed show the final designs of the skids as built.
When the guidance to the DOE Order will be issued, a training program will be developed in accordance with the Laboratory implementation plan.

SAFETY OPERATION OF SKIDS

The water safety operation is protected from system malfunctions by several interlocks. The volume, the flow, and the temperature of the water are monitored and are interlocked with the electric power source to the pumps. Any readings outside the set range will shut off the pumps.
Below are the list of the interlocks. Detailed electrical design and connections are given in the " Interlock NIM Module" 0231.00-ED-281614 and 0231.00-EC-281098; see also Appendix B "Instrumentation and Control".

Module Distribution Skid Interlocks

1- Expansion Tank High Level (90%)
2- Expansion Tank Low Level (20%)
3- Return LCW Flow (Window, 60 - 300 Gpm)
4- Supply LCW Temperature- Tc (100° F)
5- Klixon Pump/Water Temperature (Op 120°- Cl 90° F)

Module Temperature Control Skid Interlocks

1- Distribution Skid Pump Interlock
2- Module Return LCW Flow (Window, 80-260 Gpm)
3- Klixon Pump/Water Temperature (Op 90°- Cl 80° F)

MAINTENANCE OF WATER EQUIPMENT

Typical equipment inspected monthly:

Close-Coupled Pumps

Check to changes in the sound of a running pump
Changes in bearing temperature
Mechanical seal box leakage

Strainers and Filters

Check pressure drop increase across components

Water Level

Check the water level of the expansion tank in the Module Distribution Skid. The local alarm is set at about 40% level.

LCW Conductivity check (normal resistance 5 M-Ohm-cm.)
Replace DI bottles as required.

Maintenance Required Yearly:

Pump Motors Lubrication and Shaft Rotation Inspection

Clean Stainless Steel Strainers

Change 5 microns Cartridge Filters

Water Sample Analysis

SKID'S INSTRUMENTATION PANEL AND REMOTE READOUTS

Each skid has a local instrumentation meter panel to display the parameters shown on figures 4 and 7. The local readouts are used during maintenance to detect any problems out of the normal operation. Some of the parameters are sent to the computer for remote readouts and temperature controls. The charts below are typical parameters available at the control room and computers along the Linac Gallery Annex.

K7 LCW Copied 10/08/1993 09:06:47

SHOW CHAN 10/08/1993 09:06:33 STATUS 0 2 ????

W7TNOM	27 NOM TEMP	...	26.799	_	C	ON...
W7TSET	27 TEMP LP SET	*	26.401	_	C	
W7TA	27 SECTION A TEMP	*	26.455	_	C	
W7TB	27 SECTION B TEMP	*	26.342	_	C	
W7TC	27 SECTION C TEMP	*	26.404	_	C	
W7TD	27 SECTION D TEMP	*	26.383	_	C	
W7CTMP	27 CLCW SUP TEMP	...	14.996	_	C	
W7MTMP	27 MOD SUP TEMP	*	25.769	_	C	
W7PSUC	27 PUMP SUC PRES	*	21.368	_	PSI	
W7PDIS	27 PUMP DIS PRES	...	60.714	_	PSI	
W7MRET	27 MOD RET PRES	...	24.373	_	PSI	
W7MSTR	27 MOD STRN PRES	*	0.887	_	PSI	
W7CSUP	27 CLCW SUP PRES	...	56.429	_	PSI	
W7CSTR	27 CLCW STRN PRES	...	0.073	_	PSI	
W7MFLW	27 MODULE FLOW	*	164.453	_	GPM	
W7CFLW	27 CLCW FLOW	*	3.651	_	GPM	
W7VSET	27 CLCW VALVE	*	6.320	_	VOLT	
W7FSET	27 FLOW LP SET	*	3.714	_	GPM	

Typical Module Temperature Control Skid Remote Parameter Readouts

Distribution LCW Copied 10/08/1993 15:16:10

SHOW CHAN 10/08/1993 15:15:36 STATUS 0 ? ????

W1DTC1	CHILL IN TEMP	*	42.725	_	DEGF
W1DTC2	LCW SUPPLY TEMP	*	61.003	_	DEGF
W1DP1	SUPPLY PRESSURE	*	127.963	_	PSI
W1DP2	RETURN PRESSURE	*	18.882	_	PSI
W1DRES	RESISTIVITY	*	3.329	_	M/CM
W1FLOW	CHILLED WATER FL	*	130.182	_	GPM
W1LCWF	CHILLED LCW FLOW	*	129.434	_	GPM

Module Distribution Skid Remote Parameters Readouts

A P P E N D I X   A

TEMPERATURE (or FREQUENCY) CONTROL SYSTEM

Jim Crisp and John Satti

For a cavity constructed of a single metal, the percentage change in resonant wavelength equals the percentage change in linear dimension, which is proportional to temperature.

Temperature Sensitivity	-14.3 KHz/^{o}C	17.8 ppm/^{o}C of 805 MHz

The total radiation exposer inside the cavity enclosure is expected to be 10^8 rads over the 20 year lifetime of the linac upgrade. To eliminate the effects of radiation damage, the water system is located outside of the enclosure and 200 GPM of LCW, (or low conducting water), is circulated through 200 feet of pipe between the cooling skid and the cavity. The cavity copper temperature is controlled by allowing a measured amount of CLCW, (or chilled LCW), to replace an equal amount of circulating LCW at the cooling skid.

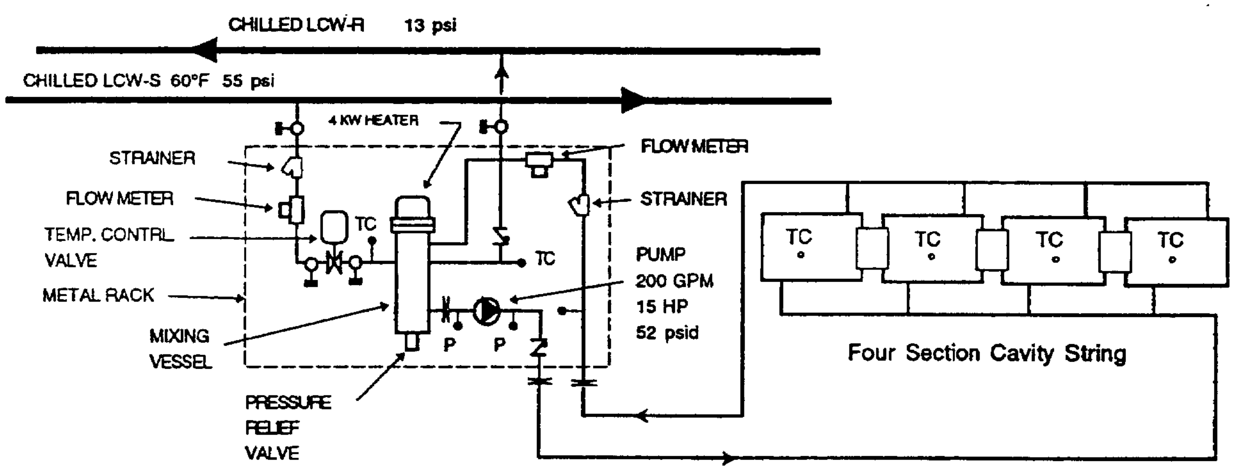


Figure 1. Schematic of cavity string cooling skid.

Under normal conditions there will be a peak rf power of 7.5 MW dissipated in the cavity copper. With a 60 usec pulse width and 15 Hz repetition rate the average rf power is 6.75 KW. In comparison, the pump required to circulate the 200 GPM between the cavity and cooling skid will dissipate 7.5 KW in the water. The cavities are expected to run near room temperature to render radiation and convection losses negligible

Power	rf power	6.75 KW
	pump power	7.5
	total	14.25 KW

Thermal mass	155 Gallons of H_2O	2.44 MJ/^{o}C
	6800 lbs Cu	1.20
	1360 lbs Fe	.28
	total	3.92 MJ/^{o}C

open loop 1/e time constant 2751 seconds 45.9 minutes

The Temperature control loop was implemented inside the local station computer. Since the parameters required to control the cavity temperature should be monitored through the computer already, only software is required to implement the loops. Because the computer also monitors rf power and waveguide to cavity phase, implementing feedforward and the separate phase loop was simplified over a stand alone controller.

The control loop is a simple integral controller selected for its zero steady state error. The closed loop bandwidth is limited to .001 Hz by the 88 second time constant formed by the film coefficient and the 48 second water travel time. The 1/e closed loop time constant of 160 seconds is about 17 times faster than the open loop.

closed loop 1/e time constant 160 seconds

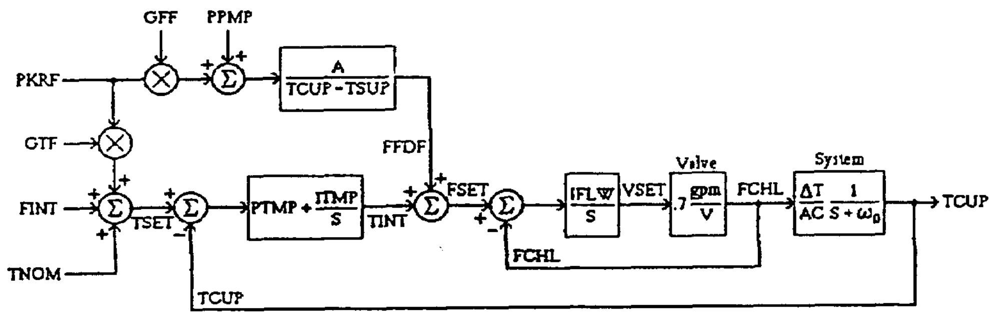


Figure 2. Block diagram of temperature control loop.

Large closed loop bandwidth, or open loop gain, is desirable to reduce the effects of unpredictable changes in the system. Predictable changes can be reduced with feedforward. Accurate control of the CLCW flow was obtained by inclosing the control valve in a separate loop using a precision flow turbine. Measured rf power, cavity, and CLCW temperatures are used to program the flow directly. Over a 4 day period the cavity temperature was observed to change by less than .07 ^{O}C and the resonant frequency by 600 Hz, (.8ppm of 805 MHz).

Water is a good thermal insulator. At the inside surface of the cooling tubes attached to the cavity, water moves slowly which allows a thermal barrier to form. Higher flow rates induce turbulence which reduces the thermal gradient but increases erosion of the cooling tubes. The 1/2 inch copper tubing used on the cavities is internally finned to improve the film coefficient. The resulting thermal resistance is 240 Watts/^{O}C at 2.9 GPM per cooling path, 50% better than smooth copper tube. The 68 cooling paths and the 6.75 KW of rf power conspire to induce a .41 ^{O}C temperature gradient between the cavity surface and the cooling water. The total flow rate of 200 GPM provides a .13 ^{O}C temperature difference between supply and return. The 34

PSI pressure drop across the cavity contributes an additional .06 °C to this difference. To minimize the temperature gradients, supply and return are reversed on neighboring cooling tubes.

The nominal rf power produces a 1.84 °C temperature gradient between the cavity nose cones and the cooling tube. The corresponding frequency change is -14.9 KHz and the 1/e time constant is 43 seconds for a step change in power. The 39 KJ/°C thermal mass of the nose cones represents only 1% of the total system thermal mass. To keep the frequency constant during turn on, 95 KW of cooling, or heating for turn off, would be required to control the temperature of the remaining 99%. A more cost effective solution is to maintain the bulk of the thermal mass at that temperature which provides the desired resonant frequency for nominal power and program the frequency during turn on. Presently the frequency program is calculated by the computer from the cavity temperature and a running average of the rf power. When the calculated frequency is within 2 KHz of the nominal frequency, the program snaps to the nominal value and the phase loop is enabled. The slower phase loop adjusts the cavity operating temperature to minimize the waveguide to cavity phase error.

Recent tests demonstrate that for a step change in power of 1 to 7.5 MW peak, only 50 seconds were required to reach within 2 KHz of the nominal operating frequency. The maximum waveguide to cavity phase error of 3° (2.2 KHz), is well within the 25° range of the low level rf system.

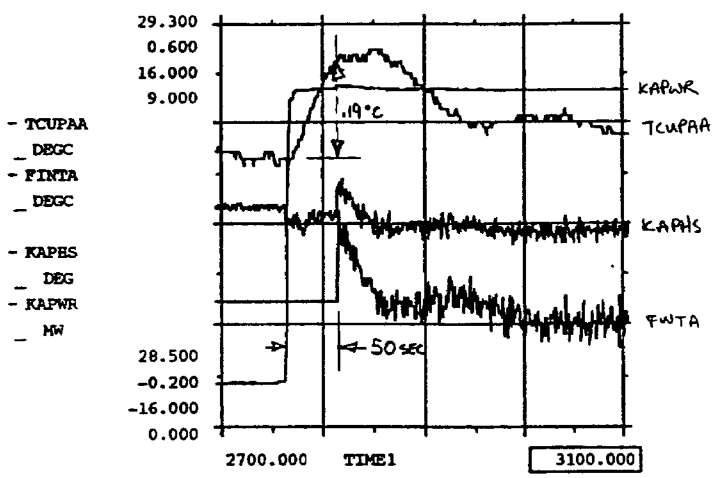


Figure 3. Step response for a 1 MW to 7.5 MW power change.

With 50 mAmps of beam current and 32° accelerating angle, the cavity resonant frequency should be 2.8 KHz below the drive frequency to keep the total cavity current in phase with the voltage. This will require running the cavities .2 °C warmer.

REFERENCES:

Crisp, J., Satti, J., "Fermilab Linac Upgrade Side Coupled Cavity Temperature Control System", to be published, 1991 PAC, May 1990.

Crisp, J., "Temperature Control Feedback Loops for the Linac Upgrade Side Coupled Cavities at Fermilab", Fermilab TM 1698, Oct. 1990.

APPENDIX B

LINAC CAVITY LCW COOLING SKIDS
TABLE OF CONTENTS

MODULE TEMPERATURE CONTROL WATER SKIDS
Instrumentation and Control
Si Fang (10-15-1992)

1. Introduction

The cavity LCW cooling skids consist of a module distribution skid, seven cavity module skids, and two module transition skids. The module distribution skid supplies $60^{o}F$ low conductivity water (LCW) to the seven cavity module skids and two module transition skids. The cavity module and module transition skids regulate the cavity temperature at $75^{o}F$.

2. Module Distribution Skid

2.1 Interlocks

2.1.1 LCW Flow Interlock

The module distribution skid LCW flow interlock senses the flow rate of the distribution skid $60^{o}F$ supply LCW. During normal condition, the LCW supply flow rate is approximate 200 GPM. If the flow rate is below 60 GPM, the pump will be shut off by the LCW flow interlock electronics.

2.1.2 Expansion Tank High/Low Level Interlock

The module distribution skid has a expansion tank with two limit switches installed at the upper and lower position of the tank to monitor the water level in the expansion tank. The upper switch is called *Expansion Tank High Level* and the lower switch is called *Expansion Tank Low Level.* The expansion tank high level switch is normally closed and the expansion tank low level switch is normally open. The two limit switches are closed if the water level is within the limits in the expansion tank. If the expansion tank water level is out of the range between the high and low level, the pump will be turned off by the interlock electronics.

2.1.3 Klixon Interlock

A normally closed 90 ^{o}F Klixon has been mounted on the 3 inches pipe near the 30 hp pump motor. If there is no chilled water for heat exchange or the 3 way valve does not work properly, the pump will run hot and the LCW temperature will be increased. The use of the Klixon interlock here is to turn off the pump and protect the distribution LCW system from being overheated. The klixon interlock is a backup for the LCW temperature interlock which the trip temperature is set at $100^{o}F$.

2.1.4 LCW Supply Temperature Interlock

The skid pump is also interlocked with LCW supply temperature. The temperature trip level for the LCW supply temperature interlock has been set at $100^\circ F$.The LCW supply temperature is regulated at $60^\circ F$. If for any reasons that the LCW supply temperature is out of control, the LCW supply temperature interlock will turn off the pump when the LCW temperature is greater than $100^\circ F$.

2.2 Pump Selector

Two 30 HP motors have been installed for the module distribution skid pumps. Only one pump is turned on during operation. The other pump serves as a back up unit. Each pump has its own motor starter which is interlocked with the other pump motor starter.

The pump motor starter can be turned on individually. The pump runs only 15 seconds (0-30 sec. adjustable) if it does not receive a TTL high signal (pump control signal) from the skid interlock chassis in 15 seconds after the pump started. The function of the pump selector is to select the pump motor starter that the pump control signal can go to. The pump selector protects two pumps from turning on at the same time for more than 15 seconds if two pumps are turned on by mistake. The de-selected pump will be turned off at the end of 15 seconds.

2.3 Motor Starters

There are two 30 HP motor starters (ED - 281694) for the module distribution skid. Each motor starter is housed in a NEMA 1 enclosure. A 50 amps circuit breaker, which is for incoming 480 VAC short circuit protection, is lockable and operable from outside of the motor starter enclosure. The motor starter can be turned on and turned off manually by pushing the *ON* and *OFF* switch at the front of the motor starter enclosure. Pump running status is indicated next to the On/Off switches.

The motor starting method is full voltage start. The control voltage is 120 VAC which is from 480/120 VAC transformer installed in the enclosure. The heater of the motor starter protects the pump motor from overloading. When pump #1 is selected and the motor starter *ON* switch is pressed, the contactor coil M1 is energized and M1 contacts are closed so that the coil M1 is on latched. The time delay relay (TDR1), which is operate on relay with 0-30 sec. adjustable, turns off the motor if the motor starter does not receive a pump control active signal (Pump Intlk) from a water flow interlock module by the end of 15 seconds (TDR1 set = 15 sec.) after motor started. The 15 seconds delay gives time for the skid water circulating the system so that the distribution LCW turbine flow meter electronics can measure the flow rate of the water and put out a TTL active high signal to turn on the solid state relay to overwrite the TDR1 contact.

To turn off the motor just simply requires pressing the *OFF* switch. By doing so, the 120 VAC control power is disconnected from the M1 coil and all the M1 contacts are then open.

2.4 LCW Temperature Regulation

The temperature of the supply LCW is regulated at 60 $°F$. The temperature regulation system mainly consists of a Honeywell UDC 3000 digital controller and a Worchester three way valve (series 75 electric actuator with AF17-4). The UDC 3000 digital controller controls the opening and closing of the three way valve which regulates the supply LCW temperature at $60°F$. The signal that controls the three way valve is 4 to 20 mA current signal. 20 mA opens the valve completely while 4 mA closes the valve all the way.

In order to use the UDC 3000 digital controller, its software configuration needs to be set for the application. The controller has twelve set up groups, five of which are actually used. These set up groups are called up by pressing the set up key, and the functions within each group are found by pressing the function key. The up and down arrow keys allow you to make changes in each function parameter. Refer to Honeywell UDC 3000 universal digital controller product manual for detail information. The UDC 3000 digital controller for the cavity module distribution skid has been set up in the following manner:

Group Prompt	Function Prompt	Selection or Range of Setting
TURNING	GAIN	30.0
	RATE	0.02
	RSET	1.0
	LOCKOUT	+CONF
SP RAMP	SP RAMP	DISABL
ALGORTHM	CONT ALG	PID A
	OUT ALG	CURRENT
INPUT 1	DECIMAL	XXX.X
	UNITS	DEG F
	IN 1 TYPE	K TC L
	IN 1 HI	1000
	IN 1 LO	-20.0
	PWR FREQ	60 Hz
CONTROL	POWER UP	A LSP
	ACTION	REVERSE

Table 1. Honeywell UDC 3000 Digital Controller Setup

2.5 Module Distribution Skid Parameters Display

The module distribution skid has a meter panel (ED - 281695) to display the skid parameters such as water flow rate, temperature, pressure, and resistivity. Some of these parameters signals are sent to the computer via smart rack monitor for remote readouts.

Water Flow Rate: Hydril turbine flow meter and Hydril series 710 indicator are used to measure the Chilled LCW Flow (FLCW) and Chilled Water Flow (FCHL). The full scale of the turbine flow meter is 600 GPM and the indicator puts out 4 mA at 0 GMP and 20 mA at 600 GPM. A 500 Ω resistor is added across 4 and 5 of the terminal at the back of the indicator to convert the 4-20 mA current signal to 2-10 V voltage signal. The formula to convert the water flow raw volt to GPM reading is:

$$\text{GPM Reading} = 600/8\ (\text{Water Flow Raw Volt} - 2)$$

where the water flow raw volt is the 2-10 V signal from the indicator.

Temperature: Omega DP41-TC-A digital meters are used to measure the Chilled In Temp (T/C1) and LCW Supply Temp (T/C2) temperature. These signals are available for remote readouts. The meters put out 0-10 V for the temperature between -299.9 $^\circ F$ and 1400 $^\circ F$. The formula to convert the temperature raw volt to temperature reading is:

$$\text{Temp Reading } (^\circ F) = (1400 + 299.9)/10\ (\text{Temp Raw Volt}) - 299.9$$

The configuration for the Omega DP41-TC-A digital meters have been set up in the following manner. The unspecified menus here are the factory set values by default (refer to DP41-TC-A product manual for detail).

MENU	SUB MENU 1	SUB MENU 2	DESCRIPTION
INPUT	TC	K	K Thermocouple
DEC PT	FFFF.FF	-	Decimal point
OUT.CNF			Output configuration
	OUT.1=1	-	Analog out enabled
	OUT.2=0	-	0-10V
OT.SC.OF:			Output scale & offset
	READ 1	-299.9	
	OUTPUT 1	00.0000	
	READ 2	1400.0	
	OUTPUT 2	10.0000	
L1 CNF:			Lockout configuration 1
	L1C.7=1	-	Type of input locked
	L1C.8=1	-	Input selection locked
L3 CNF:			Lockout configuration 3
	L3C.7=1	-	OUT.CNF locked
	L3C.8=1	-	OT.SC.OF locked

Table 2. DP41-TC-A Digital Meter Configuration

Omega 650 digital meters are used to indicate the Chilled Out Temp (T/C3) and Return Temp (T/C4) temperature. The meters are $^\circ F/^\circ C$ selectable and they are selected for $^\circ F$ reading unit.

Pressure: Omega DP41-S-A digital meters are used to display the Supply Pressure (P1) and Return Pressure (P2). These signals are available for remote readouts. Each meter has 10 Vdc excitation source for its 0-200 psi (0-100mV) pressure transducer. The meters can be configured for different applications. The Omega DP41-S-A digital meters have been set up as following:

1. 0-100 mV Selection: Jumper S2A, S2F, and S2M

2. 10 V Excitation: Jumper S4A, S2N, and S2T

MENU	SUBMENU	SET VALUE
RDG.CNF	RDG.1=1	-
	RDG.4=1	-
RDG.SC	-	0.00200
RDG.OF	-	000.000
IN CNF	INP.2=1	-
	INP.3=0	-
	INP.6=1	-
	INP.7=0	-
IN.SC.OF	INPUT 1	000.000
	READ 1	000.000
	INPUT 2	200.000
	READ 2	200.000
DEC PT	-	FFF.FFF
OUT.CNF	OUT.1=1	-
	OUT.2=0	-
OT.SC.OF	READ 1	000.000
	OUTPUT 1	00.0000
	READ 2	200.000
	OUTPUT 2	10.000

Table 3. DP41-S-A Digital Meter Configuration

Omega DP 52 digital meters are used to display the pressure of Pump Suction (P3), DI (P4), Pump Discharge (P5), Chilled In (P7), and Chilled Out (P6). The input voltage range of the DP 52 meter is selected for 0-10 V. A amplifier with the gain of 100 has been used with the meter in order to be compatible with 0-100 mV output pressure transducer (0-200 psi). The formula to convert the pressure raw volts to DP 52 meter Psi reading and the setting for the Omega DP52 digital meters is summarized as following:

$$\text{Pressure Reading (psi)} = 20.0 * (\text{Pressure Raw Volt})$$

Function	Jumper Position
0-10 V Input Selection	S3-B
10 Vdc Excitation	S4-A, S2-B,S2-D
Decimal Point XXX.X	S1-C
115 Vac Power	W1,W3

Table 4. DP52 Digital Meter Setup

Resistivity: Foxboro 874RS resistivity meter is used for measuring and displaying the resistivity of the supply LCW. The resistivity is also available for remote readouts. The meter has the resistivity measurement range of 0 to 18.3 $M\Omega \cdot cm$ with the corresponding output of 0 to 10 V. Refer to Foxboro instruction book for detail information. The formula to convert the resistivity raw volt to $M\Omega \cdot cm$ is:

$$\text{Resistivity } (M\Omega \cdot cm) = 18.3/10 * \text{Resistivity Raw Volt}$$

2.6 Skid Pumps Interlock

The module skid pump interlock enables the module skids and module transition skids interlocked with the module distribution skid pump. The pumps of the module and transition skids can not be turned on if the distribution skid pump is off. There is 3 minutes delay for the module and transition skid pumps turn off after distribution skid pump was turned off. The delay gives the distribution pump motor time to be switched with the other distribution pump motor without turning off the module and module transition skids if the distribution pump motor needs to have service.

Refer to Cavity Module Distribution Skid 30 HP Motor Starters (ED-281694) for the explanation in this paragraph. A CH series Potter & Brumfield delay on release relay is used for each motor starter to detect the pump motor ON/OFF status. TDR3 is for pump 1 and TDR4 is for pump 2. If the distribution skid interlocks are o.k and the pump 1 is selected to be turned on, the TDR1 normally open contact closed and turn on the delay on release relay (TDR3) external control switch. The TDR3 normally open contacts closed and sent a pump interlock OK signal to the Module Distribution and Module Skid Pumps Interlock Chassis (in the drawing of ED-281696) to enable motor starter interlock of the module and module transition skids. When the distribution skid pump is turned off, The external control switch is off and the delay period begins. The TDR3 delay has been set at 180 seconds. At the end of the delay period the relay drops out and all the TDR3 normally open contacts open. The distribution and module skid pumps interlock chassis received a pumps interlock NOT OK signal and turn off the pumps of the module skids and the module transition skids. Similarly, The TDR4 does the samething as the TDR3 does if pump 2 is selected. The distribution pumps (pump 1 and pump 2) ON/OFF status is ORed together and the INTLK OUT signal is sent to the distribution and module skid pumps interlock chassis.

When the distribution and module skid pumps interlock chassis received the INTLK active signal(contact closed) from the motor starter, the relay K1, K2, and K3 are energized and their normally open contacts are closed. The closed contacts enable the module and transition skids pump starters interlock circuitry.

3. Cavity Module Skids

3.1 Interlocks

3.1.1 Module Skid Pumps Interlock

The function of the module skid pumps interlock is to protect the module skids from being overheated due to no chilled LCW from the distribution skid. The module skid pumps need to wait for 15 seconds in order to turn on after the distribution skid pump started. The skid pumps are shut off if the distribution skid pump stops running for more than 180 seconds.

3.1.2 Klixon Interlock

A normally closed 90 $^{\circ}F$ klixon has been installed at 2 inches pipe near the 15 HP pump motor for each of the module skids. The klixon interlock here sets the cavity module supply LCW maximum temperature at 90 $^{\circ}F$. The skid pump is shut off by the klixon interlock if the skid out LCW temperature is out of control (higher than 90 $^{\circ}F$). The klixon can reset itself at 80 $^{\circ}F$ after it opened.

3.1.3 Motor Starter Door Interlock

Each motor starter access door is interlocked with its pump to prevent personnel from accidentally touching with 480 VAC. Open the door shuts off the skid pump and removes the 480 Vac power (except the line side of the circuit breaker) from the motor starter enclosure.

3.1.4 Cavity Water Flow Interlock

Each RF station 24 MW power modulator is interlocked with its cavity module cooling water flow. The trip level of minimum water flow rate has been set at 80 GPM and maximum water flow has been set at 260 GPM for the cavity module skids. The cavity water flow interlock signal comes from the module LCW turbine flow meter NIM module (0231.00-EC-281098) located in the cavity module skid and goes to the interlock chassis of LKx-1 rack.

3.2 Motor Starters

There is one 15 HP motor starter (EC - 281697) for each of the cavity module skids. The motor starter is housed in a NEMA 1 enclosure. A 30 amps circuit breaker, which is for incoming 480 VAC short circuit protection, is lockable and operable from outside of the motor starter box. The motor starter can be turned on and turned off manually by pushing the *ON* and *OFF* switch at the front of the motor starter enclosure. Pump running status is indicated next to the On/Off switches.

The pump motor starting method is full voltage start. The control voltage is 120 VAC which is from 480/120 VAC transformer installed in the enclosure. The heater of the motor starter protects the pump motor from overloading. When the *ON* switch is pressed, the contactor coil M is energized and M contactors are closed so that the coil M is on latched. The time delay relay (TDR), which is operate on relay with 0-30 sec. adjustable, turns off the pump if the motor starter does not receive a pump control active signal from a water flow interlock module by the end of 15 sec. (TDR set = 15 sec.) after motor started. The 15 sec. delay gives the time for the skid water flow ready so that the water flow meter electronics can measure the flow rate of the water and put out a TTL active high signal to turn on the solid state relay to overwrite the TDR contact.

To turn off the motor just simply requires pressing the *OFF* switches. By doing so, the 120 VAC control power is disconnected from the M coil and all the M contacts are open.

There are two interlock input twinax connectors mounted on the motor starter enclosure. One input is for module distribution skip pump interlock and the other input is for 90 $^{\circ}F$ klixon interlock. To turn on the skid pump, the module distribution skid pump interlock, the klixon interlock, and the motor stater door interlock must be completed. Once the skid pump is turned on, it will run for the next 15 seconds and stay on if the cavity water interlock is ready in this 15 seconds.

3.3 Temperature Control

The temperature of the cavity modules supply LCW is regulated at 75 $^{\circ}F$. The temperature regulation system for each of module skid mainly consists of thermocouple amplifier, pressure amplifier, module LCW turbine flow meter, three way control valve and the computer system for temperature regulation calculation. The 0 to 10V signal from the computer controls the open (10V) and close (0V) of the three way valve for temperature regulation.

3.3.1 Thermocouple Amplifier

The thermocouple amplifier measures the signals from the K type thermocouples and outputs -10V to +10V for the temperature range of 0 $^{\circ}C$ to 50 $^{\circ}C$. The -10V to +10V temperature signals are sent to the computer system via smart rack monitor for temperature regulation and remote readouts. There are six channels for the thermocouple amplifier. These channels are summarized in table 5.

Channel	Signal	Description	Unit	Temp. Range	Output range
1	TSECA	Section A Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
2	TSECB	Section B Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
3	TSECC	Section C Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
4	TSECD	Section D Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
5	TCSUP	CLCW Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
6	TMSUP	CAV Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V

Table 5. Thermocouple Amplifier Signals

3.3.2 Pressure Amplifier

The pressure amplifier measures the pressure from the pressure transducers and outputs 0 to +5V for the range of 0 to 200 psi (0 to 150 psi for cavity module skid #3). The pressure amplifier also supplies +5 volts excitation for the pressure transducers. The 0 to +5V pressure signals are sent to the computer system via smart rack monitor for remote readouts.There are six channels for the pressure amplifier. These channels are summarized in table 6.

Channel	Signal	Description	Pressure Range	Output range
1	PSUC	Pump suc pressure	0 - 200 psi	0 - +5V
2	PDIS	Pump dis pressure	0 - 200 psi	0 - +5V
3	PMRET	Mod ret pressure	0 - 200 psi	0 - +5V
4	PMSTR	Mod strn pressure	0 - 200 psi	0 - +5V
5	PCSUP	CLCW sup pressure	0 - 200 psi	0 - +5V
6	PCSTR	CLCW strn pressure	0 - 200 psi	0 - +5V

Table 6. Pressure Amplifier Signals

3.3.3 Module LCW Turbine Flow Meter

The module LCW turbine flow meter measures the water flow rate of cavity module LCW (*FCAV*) and the cavity module skid chilled LCW (*FCHIL*). The module skid pump is interlocked with FCAV. The FCAV minimum flow trip level has been set at 80 GPM and maximum flow trip level is 260 GPM. The module LCW turbine flow meter puts out 0 to 10 V (0 - 600 GPM) for the cavity water flow (FCAV) and 0 - 10 V (0 - 75 GPM) for the module skid chilled LCW (FCHIL).

3.4 Skid Parameters Display

The skid parameters are sent back to the computer system both for temperature regulation and remote readout via the smart rack monitor installed in each of the skids. The thermocouple amplifier module puts out -10 to +10 volt for the temperature of 0 to 50 ^oC (32 ^oF - 122 ^oF). The pressure amplifier sends out 0 to 5 volts for the pressure from 0 psi to 200 psi (0 to 150 Psi for cavity module skid #3). The module LCW turbine flow module channel A (cavity module supply LCW flow) has 0 to 10 volts output corresponding to 0 to 600 GPM and channel B (chilled LCW flow) puts out 0 to 10 volts for the chilled LCW flow rate of 0 to 75 GPM.

The skid parameters are also available for local readout. A skid parameters display chassis (ED-281685) has been installed for converting the parameters raw voltage signals to engineering unit readings. The input signals of the parameters display chassis come from the SMR outputs of the thermocouple amplifier, pressure amplifier, and module LCW turbine meter. The scaling circuit of the display chassis scales the inputs properly and the scaled signals are converted to ^oF (temperature), psi (pressure), and GPM (water flow rate) readings by using Acculex DP-352 digital panel meters.

The input voltage range of Acculex DP-352 digital panel meters is $\pm$ 2 V and the full scale input span is 199.9 with DP1 decimal point selection and 1999 without decimal point selection. The equations to convert the voltage signals (temperature, pressure, flow rate) to engineering unit readings are:

$$\text{Temperature Reading } (^oF) = 4.5 * (\text{Temp Raw Volts} + 10) + 32$$

$$\text{Pressure Reading (psi)} = \text{K1} * \text{Pressure Raw Volt}$$

$$\text{Flow Rate Reading (GPM)} = \text{K2} * \text{Flow Raw Volt}$$

where K1 = 40.0 for the pressure transducers with full scale of 200 psi, K1 = 30.0 for the pressure transducers with full scale of 150 psi, K2 = 60.0 for the cavity module supply LCW flow, and K2 = 7.5 for the chilled LCW flow.

4. Cavity Module Transition Skids

4.1 Interlocks

4.1.1 Transition Skid Pumps Interlock

The function of the transition skid pumps interlock is to protect the transition skids from being overheated due to no chilled LCW from the distribution skid. The transition skid pumps need to wait for 15 seconds to turn on after the distribution skid pump started. The skid pumps are shut off if the module distribution skid pump stopped running more than 180 seconds.

4.1.2 Klixon Interlock

A normally closed 90 $^{\circ}F$ klixon has been installed near the 3 HP pump motor for each of the transition skids. The klixon interlock here sets the cavity transition module supply LCW maximum temperature at 90 $^{\circ}F$. The skid pump is shut off by the klixon interlock if the skid out LCW temperature is out of control (higher temperature). The klixon can reset itself at 80 $^{\circ}F$ after it opened.

4.2 Motor Starters

There is one 3 HP motor starter (EC - 281684) for each of the cavity module transition skids. The motor starter is housed in a NEMA 1 enclosure. A 15 amps circuit breaker, which is for incoming 480 VAC short circuit protection, is lockable and operable from outside of the motor starter enclosure. The motor starter can be turned on and turned off manually by pushing the *ON* and *OFF* switch at the front of the motor starter enclosure. Pump running status is indicated next to the On/Off switches.

The pump motor starting method is full voltage start. The control voltage is 120 VAC which is from 480/120 VAC transformer installed in the enclosure. The heater of the starter protects the pump motor from overloading. When the *ON* switch is pressed, the contactor coil M is energized and M contactors are closed so that the coil M is on latched. The time delay relay (TDR), which is operate on relay with 0-30 sec. adjustable, turns off the pump if the motor starter does not receive a pump control active signal from a water flow interlock module by the end of 15 sec. (TDR set = 15 sec.) after motor started. The 15 sec. delay gives the time for the skid water flow ready so that the water flow meter electronics can measure the flow rate of the water and put out a TTL active high signal to turn on the solid state relay to overwrite the TDR contact.

To turn off the motor just requires simply pressing the *OFF* switches. By doing so, the 120 VAC control power is disconnected from the M coil and all the M contacts are open.

There are two interlock input twinax connectors mounted on the motor starter enclosure. One input is for distribution skip pump interlock and the other input is for 90 $^{\circ}F$ klixon interlock. To turn on the cavity module transition skid pump, the module distribution skid pump interlock and the klixon interlock must be completed. Once the skid pump is turned on, it will run for the next 15 seconds and stay on if the skid cavity water interlock is ready in this 15 seconds.

4.3 Temperature Control

The temperature of the cavity module transition supply LCW is regulated at 75 $^{\circ}F$. The temperature regulation system for each of module skid mainly consists of thermocouple amplifier, pressure amplifier, module LCW turbine flow meter, three way control valve and the computer system for temperature regulation calculation. The 0 to 10V signal from the computer controls the open (10V) and close (0V) of the three way valve for temperature regulation.

4.3.1 Thermocouple Amplifier

The thermocouple amplifier measures the signals from the K type thermocouples and outputs -10V to +10V for the temperature range of 0 °

table 7▷

Channel	Signal	Description	Unit	Temp. Range	Output range
1	TSECA	Section A Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
2	TCSUP 1	CLCW Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
3	TMSUP 1	CAV Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
4	TSECB	Section B Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
5	TCSUP 2	CLCW Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V
6	TMSUP 2	CAV Sup Temp	^oC	0 ^oC - 50 ^oC	-10V - +10V

Table 7. Thermocouple Amplifier Signals

3.3.2 Pressure Amplifier

The pressure amplifier measures the pressure signals from pressure transducers and outputs 0 to +5V for the range of 0 to 200 psi. The pressure amplifier also supplies +5 volts excitation for the pressure transducers. The 0 to +5V pressure signals are sent to the computer system via smart rack monitor for temperature regulation and remote readouts.There are six channels for the pressure amplifier but only four channels are used for the cavity module transition skid 1 and 2. These channels are summarized in table 8.

Channel	Signal	Description	Pressure Range	Output range
1	PSUC 1	Pump 1 suc pressure	0 - 200 psi	0 - +5V
2	PDIS 1	Pump 2 dis pressure	0 - 200 psi	0 - +5V
5	PSUC 2	CLCW sup pressure	0 - 200 psi	0 - +5V
6	PDIS 2	CLCW strn pressure	0 - 200 psi	0 - +5V

Table 8. Pressure Amplifier Signals

3.3.3 Cavity Module LCW Turbine Flow Meter

Two cavity module transition LCW turbine flow meters are used for cavity module transition skids. Each transition skid module LCW meter measures the flow of the cavity module LCW and skid chilled LCW (FCHIL). The expected nominal flow for FCAV is 50 GPM and the minimum flow trip level has been set at 10 GPM. The transition LCW turbine flow meter puts out 0 to 10 V (0 - 75 GPM) for the cavity module LCW flow (FCAV) and 0 to 10 V (0 - 10 GPM) for the skid chilled LCW flow (FCHIL).

4.4 Skid Parameters Display

The skid parameters for each of cavity module transition skids are sent back to the computer system both for temperature regulation and remote readouts via a smart rack monitor installed in the skid. The thermocouple amplifier module puts out -10 to +10 volt for the temperature of 0 to 50 $^\circ C$ (32 $^\circ F$ - 122 $^\circ F$). The pressure amplifier sends out 0 to 5 volts for the pressure from 0 psi to 200 psi. The transition turbine flow module channel A (cavity module supply LCW flow) has 0 to 10 volts output that is corresponding to 0 to 75 GPM and channel B (chilled LCW flow) puts out 0 to 10 volts also for the turbine meter reading 0 to 10 GPM.

The skid parameters are available for local readouts. A skid parameters display chassis (ED-281691) has been installed for converting the parameters raw voltage signals to engineering unit readings. The input signals of the parameters display chassis come from the SMR outputs of the thermocouple amplifier, pressure amplifier, and transition turbine meters. The scaling circuit of the display chassis scales the inputs properly and the scaled signals are converted to $^\circ F$ (temperature), psi (pressure), and GPM (water flow rate) readings by using Acculex DP-352 digital panel meters.

The input voltage range of Acculex DP-352 digital panel meters is $\pm$ 2 V and the full scale input span is 199.9 with DP1 decimal point selection and 19.99 with DP2 decimal point selection. The equations to convert the voltage signals (temperature, pressure, flow rate) to engineering unit readings are:

$$\text{Temperature Reading } (^\circ F) = 4.5 * (\text{Temp Raw Volts} + 10) + 32$$

$$\text{Pressure Reading (psi)} = 40.0 * \text{Pressure Raw Volt}$$

$$\text{Flow Rate Reading (GPM)} = \text{K2} * \text{Flow Raw Volt}$$

where K2 = 7.5 for the cavity module supply LCW flow, and K2 = 1.0 for the chilled LCW flow.

DRAWING SUMMARY

SKID	DRAWING TITLE	DRAWING NUMBER
DIST. & CAVITY	CAVITY LCW COOLING SKIDS WIRING BLOCK DIAGRAM	0231.00-ED-281693
MODULE DISTRIBUTION	30 HP MOTOR STARTER CIRCUIT SCHEMATIC	0231.00-ED-281694
MODULE DISTRIBUTION	PARAMETERS DISPLAY PANEL WIRING DIAGRAM	0231.00-ED-281695
MODULE DISTRIBUTION	RELAY RACK WIRNG DIAGRAM	0231.00-ED-281696
MODULE	15 HP MOTOR STARTER CIRCUITRY	0231.00-EC-281697
MODULE	RELAY RACK WIRING DIAGRAM	0231.00-ED-281698
MODULE	PARAMETERS DISPLAY CHASSIS SCHEMATIC	0231.00-ED-281685
MODULE	PARAMETERS DISPLAY BOARD SCHEMATIC	0231.00-ED-281682
MODULE TRANSITION	3 HP MOTOR STARTER CIRCUITRY	0231.00-EC-281684
MODULE TRANSITION	ELECTRONIC CONTROL SYSTEM WIRING DIAGRAM	0231.00-ED-281690
MODULE TRANSITION	PARAMETERS DISPLAY CHASSIS SCHEMATIC	0231.00-ED-281691
MODULE TRANSITION	PARAMETERS DISPLAY BOARD SCHEMATIC	0231.00-ED-281692